Mapping Southern Florida's Shallow-water Coral Ecosystems: An Implementation Plan

About This Document

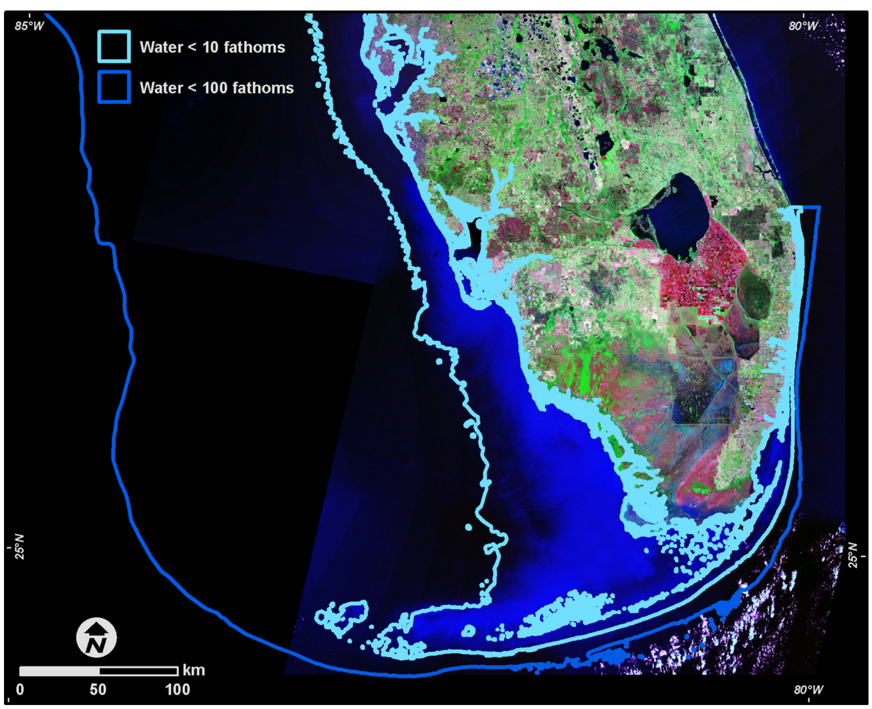
This Southern Florida Shallow-water Coral Ecosystem Mapping Implementation Plan (MIP) presents a framework for the development of shallow-water (~0-40 m; 0-22 fm) benthic habitat and bathymetric maps of critical areas in southern Florida. It also discusses the need to develop moderate-depth (~40-200 m; 22-109 fm) bathymetric maps for all of Florida. The plan has been developed with extensive input from universities, state regulatory and management agencies, federal agencies, and non-governmental organizations involved in the conservation and management of Florida's coral ecosystems. A list of organizations that provided input to the development of this MIP is provided in Appendix 1. Appendix 3 briefly presents the outcomes of two meetings where the development of this MIP was discussed.

This MIP has been developed to complement the Coral Reef Mapping Implementation Plan (2nd Draft) released in 1999 by the U.S. Coral Reef Task Force's Mapping and Information Synthesis Working Group. That plan focused on mapping the U.S.'s shallow-water (then defined as <30 m) coral reefs of the U.S. by 2007 using primarily visual interpretation of aerial photography and satellite imagery. This MIP focuses on mapping the shallow-water (now defined as 0-40 m, rather than 0-30 m) coral ecosystems of southern Florida using a suite of technologies and map development procedures. This MIP also discusses the need for shallow-water bathymetry information of southern Florida. Both this South Florida MIP and the 1999 National MIP support the goals of the National Action Plan to Conserve Coral Reefs (U.S. Coral Reef Task Force, 2000).

This MIP presents a framework for mapping the coral ecosystems of southern Florida and should be considered an evolving document. As priorities change, funding varies, new data are collected, and new technologies become available, the information presented herein will change.

Introduction

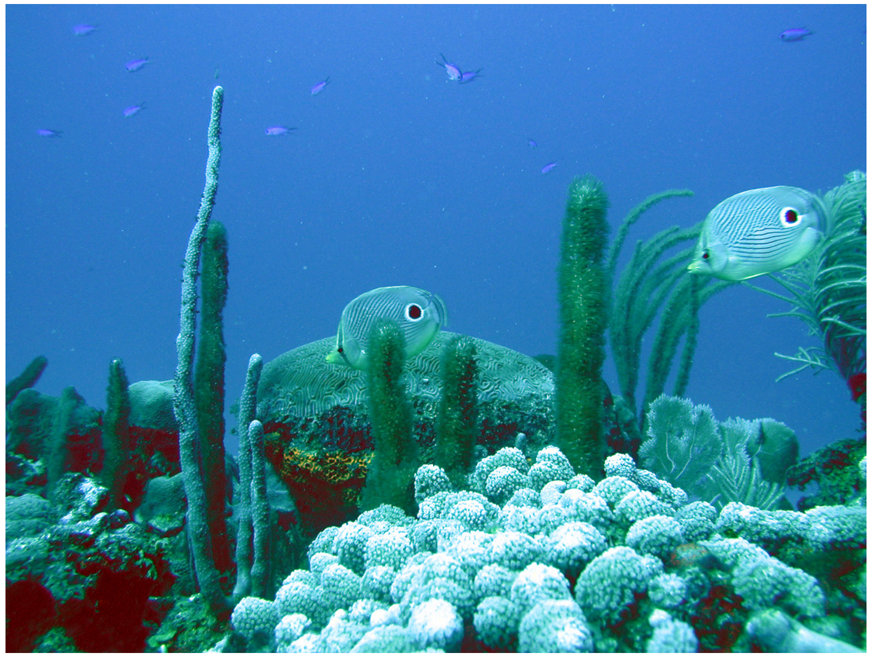
The coral ecosystems of southern Florida are extensive and represent as much as 84 percent of potential shallow-water coral ecosystems in the tropical and subtropical U.S. (Rohmann et al., in press). Using 10 fm (18 m) and 100 fm (183 m) depth curves on nautical charts as surrogates for the potential distribution of coral ecosystems, 30,801 sq km in water less than 10 fm deep and 113,092 sq km in water less than 100 fm deep respectively are found in southern Florida. While area estimates are not available for the entire 0-40 m depth regime in southern Florida, the coral ecosystems found in this region are extensive and mapping them will be a challenging task.



The location of the 10 fm (~18 m) and 100 fm (~183 m) depth curves in southern Florida.

The coral ecosystems of southern Florida contribute greatly to the region's economy. During a 12-month period from June 2000–May, 2001, reef-related expenditures generated $505 million in sales in Palm Beach County, $2.07 billion in sales in Broward County, $1.3 billion in sales in Miami-Dade County, and $504 million in sales in Monroe County, Florida. These expenditures provided 6,300 jobs in Palm Beach County, 35,000 jobs in Broward County, 18,600 jobs in Miami-Dade County, and 10,000 jobs in Monroe County, Florida

(Johns et al., 2003). A similar study using data from June 2001–May, 2002 found that, for Martin County, Florida, reef-related expenditures generated $13 million in sales and provided 182 jobs (Hazen and Sawyer, 2004). In summary, reef-related expenditures generated $4.4 billion in sales, income, and employment and created over 70,000 full-time and part-time jobs in the region during the 12-month periods when the surveys were completed.

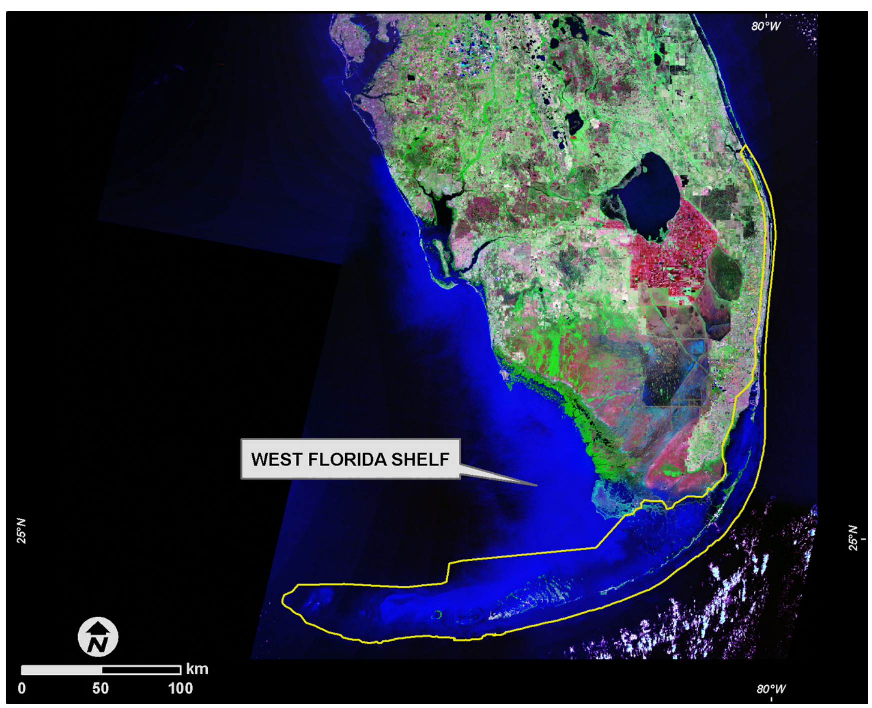


Considerable research has described the interconnectedness of the various habitat components of a coral ecosystem and the critical need for their conservation and management (Parrish, 1989; Mumby et al., 2004; Christensen et al., 2003). Research also has described the impact of over-fishing and the loss of critical habitat on coral ecosystem communities (Dulvy et al., 2004; Friedlander and DeMartini, 2002, Gardner et al., 2003). Finally, research has described the dynamics of coral ecosystem biologic communities and long-term declines of Caribbean coral ecosystems (Pandolfi, 2002; Pandolfi et al., 2003, Gardner et al., 2003). The products developed as a result of this mapping effort will support the ongoing need to evaluate the long-term condition and status of the coral ecosystems of southern Florida. These products also will support Geographic Information System (GIS) based integration of mapping and monitoring activities (Monaco et al., 2001).

Some Definitions

A coral ecosystem is composed of both habitats and structural zones. Benthic habitats found in a coral ecosystem include unconsolidated sediments (e.g., sand and mud); mangrove; submerged vegetation (e.g., seagrass and algae); hermatypic coral reefs and associated colonized hard bottom habitats (e.g., spur and groove, individual and aggregated patch reefs, and gorgonian-colonized pavement and bedrock); and uncolonized hard bottom (e.g., reef rubble and uncolonized bedrock). Typical structural zones include the reef crest, fore reef, reef flat, and lagoon (Rohmann et al., in press).

For this MIP, shallow-water will refer to the 0-40 m depth regime. This depth regime generally represents where most hermatypic coral species are found and where most direct impacts from pollution and coastal development occur. This MIP also will discuss the need to characterize moderate-depth (~40-200 m) regimes.



The yellow polygon delineates the approximately 13,000 sq km priority shallow-water benthic habitat mapping area of southern Florida.

Several general categories of mapping data or products are referred to in this MIP and brief descriptions of these are provided. Also, various technical phrases are used when discussing the acquisition and processing of data to produce bathymetry and associated habitat maps. Descriptions of these also are presented below.

—Benthic Habitat Maps: Maps that provide information about the area or environment where an organism or ecological community normally lives or occurs. The maps classify benthic habitats found on the seafloor based on geomorphology (e.g., pavement), zonation (e.g., reef crest), and biological cover (e.g., seagrass). The production of benthic habitat maps includes an independent assessment of their thematic accuracy.

—Bathymetric Maps: Maps that provide information about the depth of water from the surface to the seafloor in a water body.

—Imagery Data: Digital data that provide an indirect indication of the character of the seafloor. Sources of imagery data include backscatter data from multibeam sonar systems, side-scan sonar data, and other remotely sensed data, such as satellite or airborne imagery.

—Optical Observation Imagery: Information that represents direct observation of the seafloor and can be used to directly characterize the features found on the seafloor. When combined with bathymetric data and imagery data, optical observation imagery can be used to develop benthic habitat maps. Sources of optical observation imagery include Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), manned submersibles, Laser Line Scanning (LLS) technologies, drop cameras, and SCUBA divers. These optical validation data are important for producing benthic habitat maps.

—Multibeam data: Information acquired with a multibeam sonar system, which uses multiple acoustic signals sent out from a transducer to determine water depth and echo strength over a fan-shaped swath of seafloor. Multibeam data consists of both bathymetry (depth information) and backscatter (imagery inferred from echo strength) components.

—Bathymetric Data: Digital data measuring seafloor depth and topology collected directly by active sensors, such as multibeam sonar, single-beam sonar, and LIDAR (Light Detection and Ranging). It can occasionally be roughly inferred from passive sensors like satellite imagery.

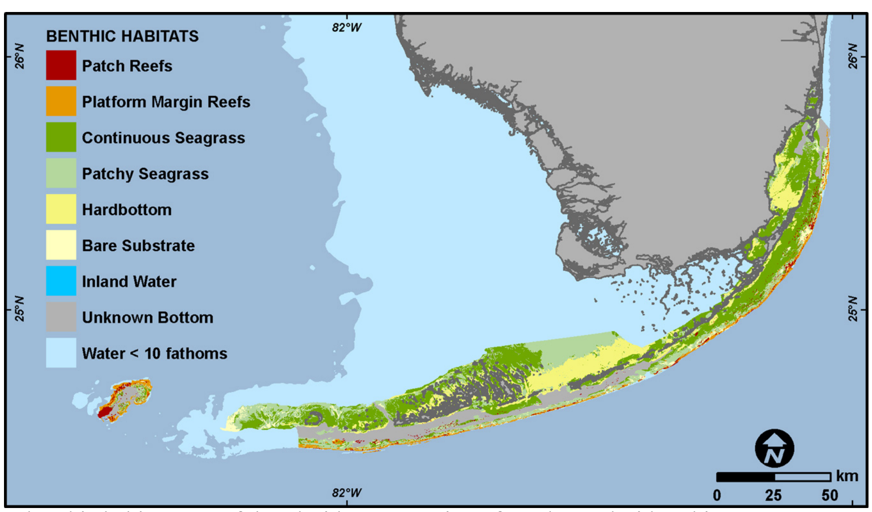
—Backscatter data: Acoustic backscatter, or the intensity time series of the bottom return from a sonar or LIDAR signal, can be derived from side scan sonars, multibeam sonars, and LIDAR data. For clarity, within this MIP the term backscatter will be applied to either multibeam backscatter or LIDAR backscatter, while information from side scan sonars will be termed "side scan sonar imagery."

Why Map?

Maps of Florida's shallow-water coral ecosystems are needed to support many federal and state conservation and management objectives, and research activities. Other uses of the maps include depicting management and conservation boundaries, characterizing essential marine organism habitat, monitoring the baseline condition of the reef ecosystems and factors affecting their condition, enforcing regulations on fishing and similar activities and, where applicable, assessing the extent and impact of marine debris on the reefs. In addition, maps will be critical for assessing changes taking place in the reef ecosystems of these areas over time.

Due to the ever-increasing impacts from activities such as construction of underwater gas pipelines, fiber optic cables, harnessing the hydrodynamic power of the Gulf Stream, establishment of new anchorages, and other potential impacts, it is critical that up-to-date benthic habitat maps be available. Resource conservation and management agencies are faced with the problem of not being able to fully assess the potential impact of these activities. Delineation of coral reef habitats and other essential fish habitat remains a high priority for many of the areas located offshore of southern Florida counties, and is necessary for developing stronger conservation measures for managed species and ecosystem-based management.

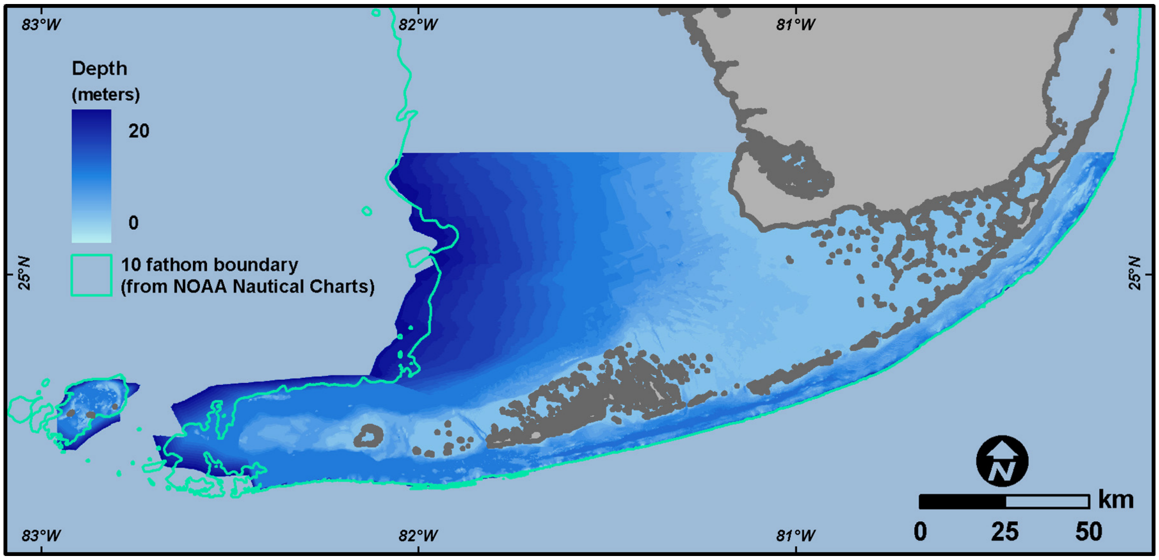
In addition to the need for benthic habitat maps of south Florida's coral ecosystems, broad interest and need exists for detailed bathymetric maps of the region. The FWRI has several management activities that could directly benefit from having detailed bathymetric data available. These management needs are described below. The Florida Keys National Marine Sanctuary (Florida Keys NMS) and the National Park Service also have indicated their need for bathymetric data to support conservation and management responsibilities. NOAA's Coral Ecosystem Mapping Team has found bathymetry data to be a valuable data set that is used extensively during the development of shallow-water benthic habitat



A benthic habitat map of the Florida Keys region of southern Florida. This map, completed in 1998 and based on aerial photography collected in 1991-1992, includes large "Unknown Bottom" areas.

maps.

Several organizations in Florida have indicated the need for comprehensive, high-resolution imagery of the coral ecosystem areas in the region. These images, whether they are aerial photography or high-resolution satellite imagery can be used for many purposes. NOAA's Coral Ecosystem Mapping Team has used either aerial photography or high-resolution satellite imagery to generate detailed benthic habitat maps of over 6,325 sq km of coral ecosystems in the US (see http://biogeo.nos.noaa.gov). Detailed imagery of the region would be a critical source of information for mapping southern Florida's shallow-water coral ecosystems, while bathymetry would be essential for mapping the deeper water coral ecosystems.



The bathymetry of southern Florida. This bathhymetry map was developed by the University of South Florida using a combination of data sources.

Management Requirements

A number of long-standing or recent mandates and legal requirements exist that are increasing the demand for mapping to be done in Florida, the southern Atlantic Ocean and the eastern Gulf of Mexico. These legal requirements exist in NOAA, the state of Florida, and other federal agencies, such as the U.S. Fish and Wildlife Service and the National Park Service. In addition, a broader user community, which includes other federal agencies, such as the U.S. Geological Survey, and numerous universities actively conduct research and monitoring activities in the southern Florida region that directly and indirectly support mandated state and federal management and regulatory activities. A summary of Federal and State management mandates is provided in Appendix 2.

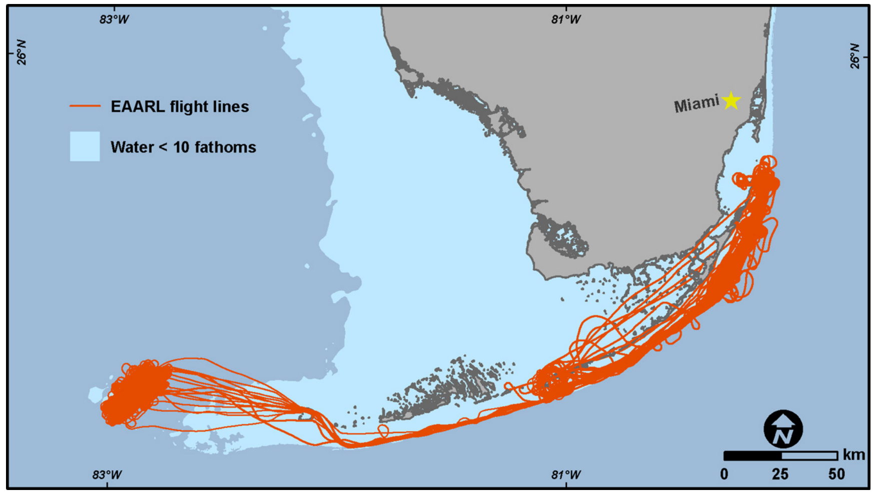
Mapping Activities

Table 1 (located at the back of this document) provides a summary of southern Florida benthic habitat characterization and mapping activities completed, in progress, or planned. In 1998, an extensive benthic habitat atlas for the Florida Keys was produced as a result of a six-year, federal-state effort to map the type and extent of bottom communities in the Sanctuary (FMRI, 2000). Over the years, this product has supported numerous research, monitoring, and management actions and provided the impetus for many other mapping efforts.

These mapping efforts have used different technologies to provide the imagery from which maps were generated, different mapping protocols to interpret the imagery, different classification schemes to characterize the features depicted on the maps, different minimum mapping units sizes (the size of the smallest feature characterized), and overlap in some cases. As a result, these map products are not easily comparable, and when combined together do not create a complete, consistently derived map.

Each of these mapping efforts was initiated to provide specific information for research, conservation, or management needs. However, the map products frequently are not comparable or useful beyond their initial requirements. For example, the 1998 FMRI map does not include information on benthic habitats in the western portion of the Florida Keys NMS. Some managers and researchers believe that a revised, standardized, high-resolution, Sanctuary-wide benthic habitat map is needed for a variety of reasons.

First, data on the previously unmapped and undescribed habitats need to be added. Second, researchers use benthic habitat maps to help identify potential study sites and, more specifically, to locate different habitat types when it is necessary to stratify sampling among habitats. Also, investigators have found some inaccuracies in the existing 1998 maps when they were used for this type of stratification. Third, for conservation and management, it is necessary to examine spatial relationships among different components of the ecosystem and in relation to important forcing functions such as ocean and coastal circulation patterns, hydrological linkages with terrestrial parts of the south Florida ecosystem, and storm events. Finally, a new ecosystem map and associated data can be used for analysis of changes, some of which have already been documented through existing monitoring projects. It would be useful for a variety of users to be able to visualize such changes using a new, higher-resolution ecosystem map. Similar, but different, inadequacies or inconsistencies can be described for many of the south Florida mapping products (see Table 1).



The locations where NASA EAARL (Experimental Advanced Airborne Research LIDAR) data have been collected in southern Florida.

An overarching goal of the U.S. Coral Reef Task Force is to preserve and enhance the living resources of U.S. coral ecosystems, including those in southern Florida. A major challenge with reaching that goal and with coral ecosystem resource management is the difficulty in discriminating natural variation in ecosystems from changes or declines caused by human impacts that may be managed, such as wastewater and stormwater treatment and disposal. Long-term data sets and research to determine thresholds that result in shifts in community structure, in conjunction with a detailed ecosystem map, are required to understand and effectively manage this large marine ecosystem. In addition, many mobile species utilize different habitat types over the course of their life histories. A new southern Florida coral ecosystem map that could be used to support analysis of the distribution of and spatial relationships among different habitat types is essential for improving our understanding of ontogenetic habitat changes and possible management actions related to protecting entire life cycles, from larval settlement through juvenile growth and adult reproduction.

Mapping Priorities

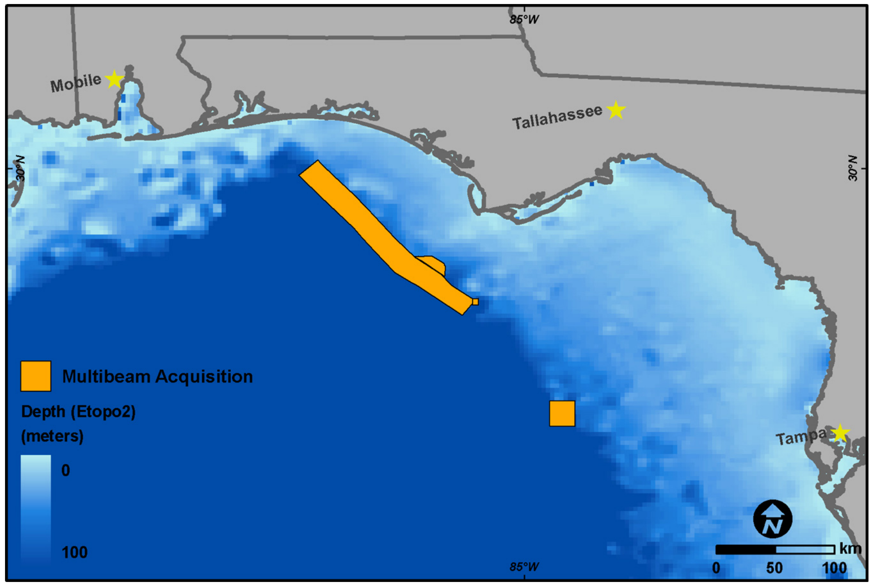
Geographic Area of Interest

The geographic area of interest—where characterization of seafloor bathymetry and shallow-water benthic habitats is needed—can be defined based on both geographic location and depth regime. The conservation, regulatory, or management requirements that form the basis for defining the geographic area of interest are discussed in the previous section.

The state of Florida needs map products and related digital data statewide to manage their coastal resources. The Florida Fish and Wildlife Research Institute (FWRI) is interested in south Florida as far north as the St Lucie River Inlet on the East Coast along the Atlantic Ocean, and as far north as the Anclote Keys on the West Coast in the Gulf of Mexico. The FWRI is interested in the Florida Keys as far west as the Dry Tortugas, including Tortugas Bank, Sherwood Forest, and Rileys Hump. FWRI needs characterization activities to extend out from the shoreline at least to 3-mile State and possibly 12-nautical mile Federal boundaries. FWRI also needs to characterize out to a water depth of 40 m, if this depth contour lies farther away from shore than other boundaries. They also recommend characterizing areas, such as Pulley Ridge, which lies in approximately 100 m deep water in the Gulf of Mexico.

The FWRI requirements overlap with those of other management agencies, such as the Florida Keys NMS. In general, the Florida Keys NMS needs to map much of Southern Florida and the eastern Gulf of Mexico in order to study and model the Gulf of Mexico loop current and related larger-scale circulation patterns and associated biologic connectivities. The Florida Keys NMS indicates the need to map the seafloor to a minimum depth of 100 m (to include the seaward boundary of the

Florida Keys NMS), and preferably to at least 600 m to include the deeper reaches of the Tortugas South ecological reserve and deeper features adjacent to the rest of the southern boundary of the Florida Keys NMS.



The locations where ship-based multibeam data have been collected in Florida.

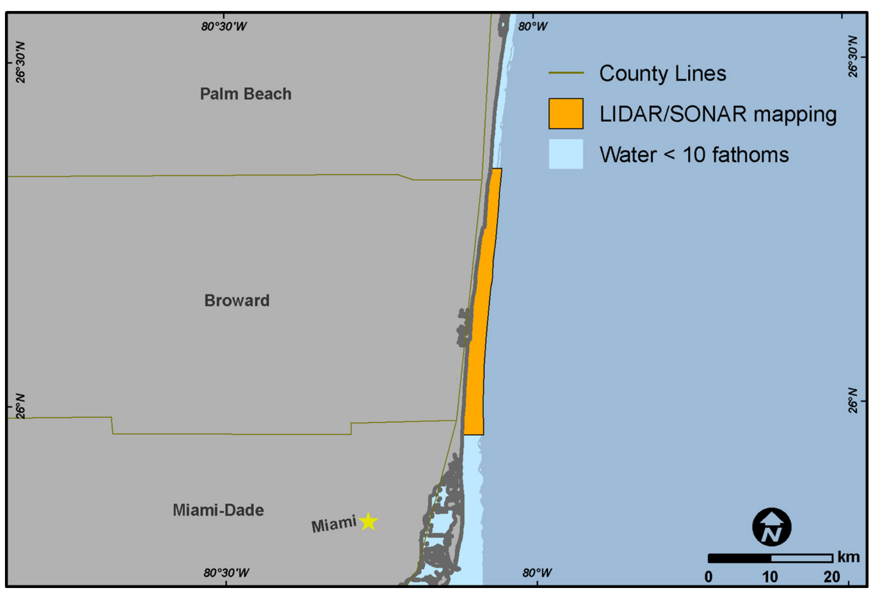
In general, state and federal management and regulatory agencies, researchers, and other organizations indicated that the 0-40 m water depth regime is the most critical for conservation and management issues in southern Florida. Within this depth regime are those components of coral ecosystems most directly affected by coastal development, commercial and recreational fisheries, and other coastal zone management-related issues. Considerable interest also exists in southern Florida coastal waters to a depth of ~200 m (~110 fm). Within this depth regime are the deeper water components of coral ecosystems, deeper water fisheries, and associated conservation and management concerns.

Minimum Mapping Unit

A minimum mapping unit—usually described in sq m—is the smallest feature (e.g., an individual patch reef) or aggregate of features (e.g., scattered coral heads on hard bottom) that is delineated using a given source of imagery (e.g., aerial photography, high-resolution satellite imagery, or LIDAR) and mapping protocol (e.g., image analysis or visual interpretation). Deciding on an MMU is a balance between providing maps with sufficient detail that meets the requirements of people using the maps and the time and cost to make the maps.

The NOAA Coral Ecosystem Mapping Team has used a MMU of ~4,047 sq m (~1.0 acre; 0.004 sq km) and visual interpretation to map the benthic habitats in Puerto Rico, US Virgin Islands, Hawaii, American Samoa, Guam, and the Northern Marianas. An MMU of ~100 sq m (0.0247 acre; 0.0001 sq km) and semi-automated image analysis was used when mapping the benthic habitats of the Northwestern Hawaiian Islands. In some areas, such as Buck Island Reef National Monument in St Croix, U.S. Virgin Islands, maps with an MMU of 100 sq m also have been produced.

Generally, the size of the MMU represents a tradeoff between the desire to map small features (e.g., individual coral heads or patch reefs) and the time required to identify and classify all the features visible in the data. The smaller the MMU, the more individual features will be mapped and, depending on the technique used to characterize the features, can increase the time required to produce the map. The ability to assess the thematic accuracy (i.e., how many of the benthic habitat features are correctly classified) also is a factor in setting the MMU size. Depending on the overall size of the study area, the biologic and structural complexity, and the MMU size of the area being mapped, hundreds to thousands of field habitat observations may need to be collected to adequately assess map thematic accuracy. Collecting these field habitat observations can be an expensive and time-consuming effort. There is broad consensus that the research, conservation, and management community using the maps very much prefers thematic accuracy to spatial detail.



The locations where the Florida Fish and Wildlife and Conservation Commission and the National Coral Reef Institute have collected LIDAR data and mapped shallow-water benthic habitats in southern Florida.

Some research, conservation, and management activities may require setting a smaller MMU than typically set for synoptic mapping efforts. This can be accomplished using digital imagery and state-of-the-art GIS and image analysis software. Mapping smaller areas using a smaller MMU is frequently done as part of spatially explicit analyses of habitat utilization by fishes or other marine organisms. The more generalized "base map" with the larger MMU can be used as the starting point for developing more detailed maps, where the more detailed habitat maps "nest" inside the more generalized base map.

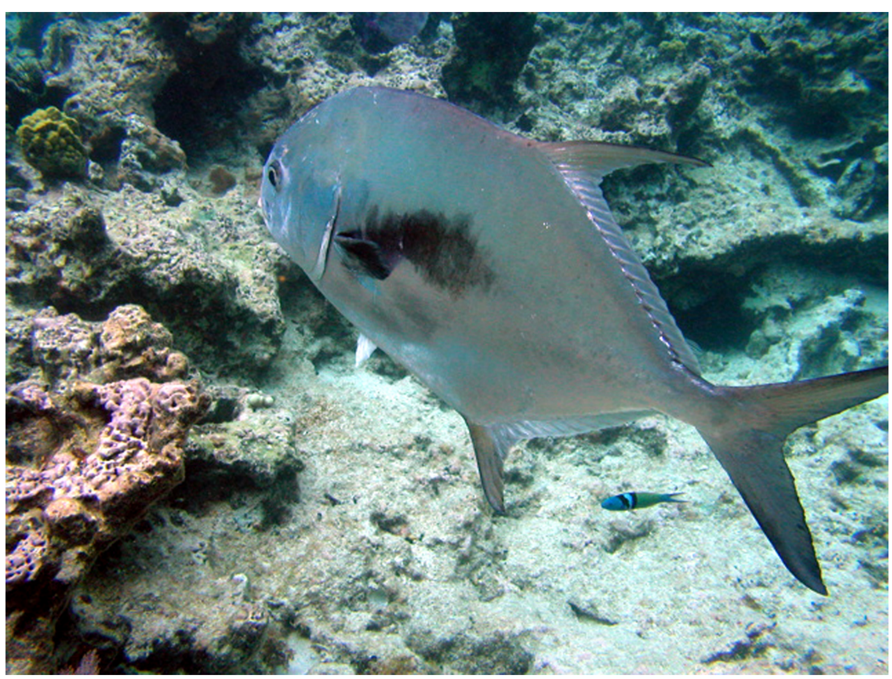
The FWRI recommends 1:24,000 scale mapping with a MMU of 0.5-1.0 acres (2,043-4,047 sq m). FWRI also recommends that, for areas where critical conservation or management issues exist, benthic habitat maps with smaller MMUs may be required. Their management requirements need maps of selected areas with MMUs as little as 4 sq m or less. The Florida Keys NMS believes that an MMU of 2,043-4,047 sq m will be adequate for extensive areas, but would like features, such as patch reefs, marine zones, confirmed and potential reef fish spawning aggregation sites, marine heritage sites, and artificial reefs less than 100 sq m in size mapped if possible.

Mapping Technologies

Several types of maps are required to meet the needs of the organizations responsible for the conservation and management of the coral ecosystems of southern Florida, and a suite of technologies will be used to collect the data needed to produce those maps. The platforms on which these technologies are deployed also are important. Some of the technologies, such as active sonar (multibeam/backscatter) instruments, are deployed on small vessels (launches) or ships, depending on the depth of the water being surveyed. LIDAR technologies are deployed on airborne platforms. This MIP will briefly describe some of these technologies, their deployment, and their strengths and weaknesses for collecting the types of data needed to produce the required maps. Other technologies, such as side-scan sonar, will not be described because their application to support this MIP is limited. Table 2 provides a summary of the technologies used to produce coral ecosystem maps. Table 3 summarizes the types of technologies available to support the development of bathymetric and benthic habitat maps.

Sonar Technology

Active sonar instruments are based on the principle of emitting sound energy and analyzing the echoes returned from seafloor features. There are three types of sonar systems of interest to habitat mapping work: vertical beam echosounder (VBES); multibeam echosounder (MBES), and side scan sonar. Of these, the multibeam systems are of primary interest and utility.



While vertical beam echosounder systems, also termed single beam sonar, can cost-effectively and efficiently collect single-point bathymetry in some areas (particularly inshore), the density and resolution of single-beam bathymetry data is insufficient to make accurate, detailed bathymetry maps without resorting to extensive interpolation. In addition, the use of the bottom characterization data from single-beam sonar for benthic habitat mapping is still in the developmental phases.

Table 3. Summary of the types of technologies available to support the development of bathymetric and benthic habitat maps. Technically, it is very difficult to map the very shallow depth (~0-2 m) portion of the coast either because sensors cannot be deployed at these water depths or wave interaction with the shore obscures the seafloor.

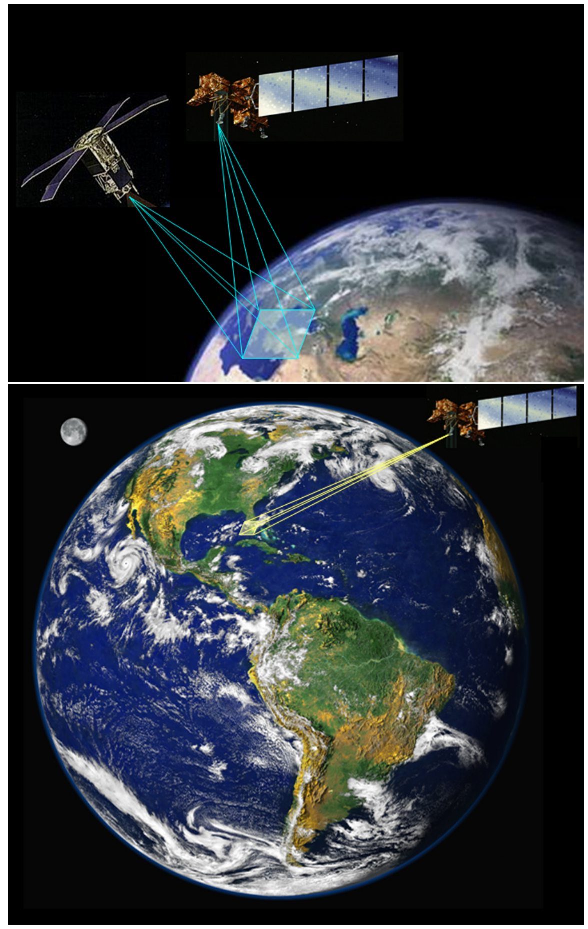
Data Type	*Technology*	2-18 m depth regime	18-183 m depth regime	183-915 m depth regime	>915 m depth regime
Bathymetry					
	LIDAR	X	to ~ 46 m		
	single beam	X	X	X	X
	multibeam	X	X	X	X
Imagery					
	aerial photography	X	to ~ 27 m		
	high-resolution satellite imagery	X	to ~ 27 m		
	multibeam backscatter	X	X	X	X
	side-scan sonar	X	X	X	X
Validation Data					
	SCUBA diver observations	X	X		
	drop cameras, ROVs	X	X	X	
	laser line scanner	X	X	X	
	multispectral satellite imagery	X			
	submersibles		from ~ 92 m	X	X

Side scan sonars provide high-resolution imagery of the seafloor, but cannot provide bathymetric depth information, which is of key importance. Typically, side-scan sonars are towed instruments that provide acoustic imagery data, but not bathymetric information (although a few very expensive systems for deep water survey do provide both types of data). Because side-scan sonars are towed instruments, the exact positioning of the data can be difficult to determine.

Unlike single beam and side scan sonars, multibeam sonars provide both spatially accurate bathymetry and imagery information over a continuous swath of seafloor. Multibeam sonars have transducers that send and receive up to 150 highly accurate and precisely located measurements of water depth spread over the swath of the instrument beneath the vessel. The information from sonar technologies that is useful for producing benthic habitat maps falls into two basic categories—bathymetry and backscatter.

Water depth, or bathymetry, is determined by measuring the time required for an underwater sound wave to reflect off the seafloor and return to the sonar instrument, and the angle of the sound wave in relation to the sonar instrument. The intensity of the returned echo also has valuable information. The strength of the echo that gets bounced off the seafloor, termed "backscatter," is a function of the incident angle of the initial sound pulse, the roughness or surface characteristics of the sea floor (e.g., coral, sand, or seagrass), and the composition or density of the bottom (e.g., rock or mud).

Multibeam bathymetry and backscatter data can be collected simultaneously using the same active sonar instrument. As mentioned earlier, these instruments are deployed on vessels and are generally hull mounted for maximum stability. The depth of the water to be surveyed determines the size of the vessel and the specific characteristics of instrument deployed. Smaller vessels are used in shallow water; larger vessels are used in deeper water. High frequency multibeam instruments are typically used to measure shallow water depths; low frequency instruments are used to measure deeper water depths. When collecting multibeam data, the general rule of thumb is that the usable width of the swath is approximately equal to three times the depth of the water. While multibeam data collection instruments can collect data up to 7.5 times the depth of the water, depending on water depth, most data collection activities assume that the swath width is between 3 and 5 times the depth of the water. For example, if the water is 10 fm (~18 m), the usable swath width is 30 fm (~55 m). If the water depth is 200 fm (~366 m), the swath width is 600 fm (~1,100 m). When collecting data, the typical speed of the vessel is 5-10 knots (~9.2-18.5 km/hr). Minimum standards for bathymetric survey data quality are set by the International Hydrographic Organization (IHO), in IHO publication S-44. Adhering to these international standards, or to any agency-specific requirements, will affect the parameters used in both acquisition and processing.



Examples of satellite collection footprints available with current earth orbiting satellites. The upper figure is an example of a Landsat 170 km X 180 km image footprint. The lower figure is an example of a high-resolution satellite image footprint (e.g., 10 km X 10 km box).

Once the data are acquired, processing of the data is conducted. Some of this processing, such as corrections of the multibeam data for sound velocity, pitch, roll, heave, tide, and ship draft is conducted aboard the ship at the time of acquisition. Other processing, such as the removal of artifacts (anomalies in the data) or biases in the multibeam data, requires more detailed and lengthy involvement and typically continues after the ship returns to port. Similar processing is performed on the backscatter data. Additional processing may be required if anomalies, such as along-line stripping, are found in the backscatter data.

By understanding those bottom features that correspond to specific depth and backscatter signatures, it may be possible to create benthic maps. This is typically done by collecting multibeam and backscatter sonar data over a region of interest and integrating them—for example, by statistically clustering backscatter signals into unique classification groups, by modeling bathymetry rugosity in relation to known ground truthing points, or by piecing together the various track lines into a backscatter "image mosaic" and correlating the mosaic to the underlying bathymetry. The specific types and number of categories of benthic features that can be mapped are a function the spatial resolution of the data collection, the sound frequency of the sonar technology, the characteristics of the bottom, and the classification technique used. Generally, sonar mapping can produce maps having between three and six (3-6) accurately delineated habitat classes (e.g., soft bottom; hard bottom; high relief; low relief).

Few maps of benthic habitats have been made using sonar technologies, as sonar-based mapping techniques are a developing field still rooted in research and development rather than mass production. It is hard to predict seafloor types from the acoustic return alone, since variable types of substratum can produce similar voltage returns of the signal, and other variables besides seafloor type can affect the acoustic return. Rigorous ground truthing (the collection of optical observation imagery or field habitat observations) is necessary to understand and interpret the meaning of patterns found in acoustic data.

The National Coral Reef Institute (NCI) has been applying single beam acoustic habitat mapping to coral reefs for several years. They have found that single beam acoustic mapping, when compared with classes obtained from commercially-available high resolution satellite imagery, corresponded with 66% producer accuracy and a 56% overall accuracy using field habitat observation data (Riegl and Purkis, 2005). However the accuracy can be increased to 90% when integrating the acoustic ground discrimination with high-resolution bathymetry and aerial photography (Walker et al., submitted). More recently, NCRI used QTC and Echoplus sensors to produce a benthic habitat map for Broward County with an 88% overall accuracy. This is an example of how acoustic surveys can provide a useful mapping product, particularly in areas where water clarity precludes the use of other methods. NCRI has presently used these technologies to map Broward County, Florida, an area of approximately 111 sq km. However, neiher acoustic bathymetry nor backscatter imagery has been used to synoptically map the benthic habitats of large geographic areas, such as southern Florida. Also, no analysis has been completed to determine how many field habitat observations would be needed to assess the accuracy of a benthic habitat map derived from acoustic sonar data. The cost of collecting sonar data (especially in shallow water—see below) and its low accuracy without integrating it with other technologies, may limit using acoustic sonar data for mapping south Florida.

Several references are available that provide estimates of the cost to collect multibeam bathymetry and backscatter and, in some cases, side-scan sonar data. These references tend to support the estimates found in Tables 4 and 5. However, it is very important to note that the cost of multibeam acquisition and processing is extremely project-specific, and will vary based on a variety of factors including water depth, project location, availability of ship resources and personnel, quality standards in effect, and whether the project is conducted internally within an organization or contracted out. Evans et al. determined that the collection of multibeam and backscatter data with side-scan sonar for three locations in the Gulf of Mexico cost an average of $4,900/sq km. NOAA Fisheries spent about $350,000 (~$310/sq km) to collect multibeam data over about 1,130 sq km of 100 m deep water in the Gulf of Mexico. Axelsson and Alfredsson report that the acquisition of Order 2 multibeam data in water 8 m deep costs an estimated $6,620/sq km. Similar data in water 16 m deep costs an estimated $1,939/sq km. Order 2 multibeam data collection in water 150 m deep costs an estimated $150/sq km.

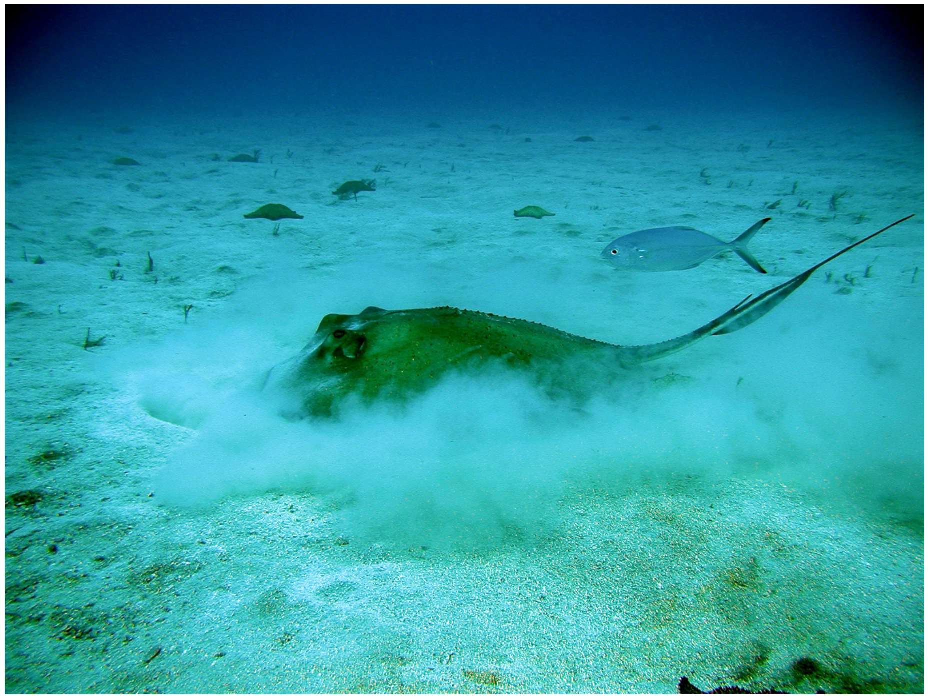


Table 4 presents the per-unit-area cost estimates and computed cost estimates for mapping various depth regimes using multibeam sonar. Table 5 provides very rough estimates of the cost to complete the collection of bathymetric data within the 18-183 m (10-100 fm) isobaths and benthic habitat maps for areas in southern Florida.

Table 4. Cost estimates for gathering and initial shipboard processing of multibeam and backscatter data. These estimates assume the following: IHO Level 2 data will be collected; the ship is traveling at 10 km/hr; the ship costs $30,000/day; the ship collects data for 10 hr/day; and the swath width is four (4) times the depth of the water. All computations were made using a 100 sq km (10,000 m X 10,000 m) area of interest. Estimates of the cost of post-processing of data are based on a cost of ~$1,000/day and the approximation that two (2) days are required to process one (1) day of multibeam data. These estimates ***do not*** *include any vessel mobilization and demobilization costs or the costs of time at sea during bad weather (which could reduce or halt data collection). Vessel mobilization can be a significant expense, often starting in the hundreds of thousands of dollars, depending on vessel readiness.*

	cost to collect data for the 2–18 m depth regime	cost to collect data for the 18–183 m depth regime	cost to collect data for the 183 m depth regime	cost to collect data for the 183–1,830 m depth regime
average water depth (m)	15	50	183	350
swath width (m)	60	200	732	1,400
number of swaths required	167	50	14	7
number of hours required	167	50	14	7
number of days required	17	5	2	1
total cost	$510,000	$150,000	$60,000	$30,000
cost per sq km.	$5,100	$1,500	$600	$300
post processing cost (per day)	$1,000	$1,000	$1,000	$1,000
cost to post-process data	$34,000	$10,000	$4,000	$2,000

In Table 5, the estimated area of coral ecosystems in southern Florida is taken from Rohmann et al. (in press). Table 5, the area inside the 18-183 m isobaths is computed by subtracting the area inside the 18 m isobath from the area inside the 183 m isobath. For example, in southern Florida, 30,801 sq km are inside the 18 m isobath and 113,092 sq km is inside the 183 m isobath. The area inside the 18-183 m isobath equals 113,092 minus 30,810, or 82,291 sq km. Existing multibeam sonar data (and, possibly, side scan sonar data) have been collected for some areas in southern Florida, but have not been incorporated into this analysis. Also, no data processing costs are included in these estimates. Generally, for every day spent collecting data, two days are needed to process the collected data to achieve a clean, final dataset. Deriving any mapping products from the cleaned data will take significantly longer.

Table 5. Estimated cost to collect multibeam and backscatter data for the area inside the 2-18 m (1-10 fm) and 18-183 m (10-100 fm) depth areas of southern Florida. The cost values presented here are derived from Table 4 and could overestimate or underestimate actual costs by 25 percent or more.

	inside the 2–18 m isobath	inside 18–183 m isobath
southern Florida area (sq km)	30,801	82,291
cost/unit area	$5,100	$1,500
estimated cost	$157,085,100	$123,436,500

LIDAR Technology

LIDAR is an acronym for Light Detection and Ranging, which is the science of using a laser to measure distances to specific points. Airborne LIDAR systems direct a short pulse of laser light from an aircraft toward the surface below. Bathymetric LIDAR measures the distance to the surface of the water and the distance to the bottom of the water body. The difference between these two measurements is the depth of the water. The LIDAR return signal does not, however, provide information about the composition of the bottom and it is this information that is important for creating benthic habitat maps.

LIDAR technologies typically are deployed on aircraft. Depending on the type of data needed (i.e., the sounding density, swath width, and swath overlap), the aircraft flies at 140-210 kts (260-390 km/hr). In clear water, LIDAR can gather bathymetry data to depths of ~20-35 fm (~35-65 m). Turbidity or other suspended material in the water column, clouds, and sea state can affect the ability of the LIDAR technology to characterize the sea floor.

The costs of acquiring airborne LIDAR data in very shallow water (2-27 m) are 25% to 50% of multibeam costs (Table 6). However, the cost advantage decreases as water depth increases (Axelsson, R. and Alfredsson, Capacity and Capability for Hydrographic Missions, Saab Dynamics AB). NOAA estimates the cost of gathering and initial processing of LIDAR data to produce bathymetry maps costs approximately $1,015/sq km. Other studies indicate that the collection and processing of LIDAR data to produce bathymetry can cost as much as $2,330-$2,915/sq km (Final Report: Early Implementation of Near-shore Ecosystem Database Project, 1999; Moss Landing Marine Laboratories and California State University, Monterey Bay, CA.).

Table 6. Cost estimates for gathering and initial processing of aircraft-based LIDAR data for the area inside the 2-18 m (1-10 fm) depth regime of southern Florida. The posting density (e.g., 3 X 3 m) defined during LIDAR acquisition affects the acquisition swath width. The overall cost values presented could overestimate or underestimate actual costs by 25 percent or more. The data acquisition cost estimates were provided by David Miller, Vice President-Coastal Mapping and LIDAR Services, Fugro Pelagos, Inc. NOAA calculated the overall estimated cost values.

	range of acquisition costs	average acquisition cost	area of 2-18 m depth curve	overall estimated cost
5 X 5 m postings	$225-$525/sq km	$375/sq km	30,801sq km	$11,550,375
4 X 4 m postings	$325-$850/sq km	$585/sq km	30,801 sq km	$18,018,585
3 X 3 m postings	$575-$1400/sq km	$985/sq km	30,801 sq km	$30,338,985
2 X 2 m postings	$1200-$2800/sq km	$2000/sq km	30,801 sq km	$61,602,000

These estimates include some, but not all, aircraft mobilization and demobilization costs and some of the costs when the aircraft sits on the tarmac during bad weather (which would halt data collection).

If only bathymetric data are required, airborne LIDAR is a viable technology in water down to ~30 fm (55 m) depths. As with multibeam sonar, LIDAR technologies can acquire LIDAR backscatter, which may be valuable for benthic habitat mapping. A limited amount of research, primarily by NCRI in Florida, has evaluated the potential of LIDAR (in this case LADS), but not LIDAR backscatter, for mapping benthic habitats. However, protocols to produce synoptic benthic habitat maps of large geographic areas, such as southern Florida, currently do not exist.

Satellite Imagery

Satellite imagery is a valuable tool for natural resource managers and researchers. It provides a snapshot record of the location and extent of habitats at a point in time. NOAA has produced benthic habitat maps of the Northwestern Hawaiian Islands, American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands, and is currently producing benthic habitat maps of the main Hawaiian Islands and Palau using visual interpretation of multispectral, high-resolution, IKONOS satellite imagery and the NOAA Habitat Digitizer extension. Habitat boundaries are delineated around signatures (e.g., areas with specific color and texture patterns) in the orthorectified imagery mosaic corresponding to habitat types associated with a locally specific Classification Scheme. The custom Habitat Digitizer extension is used, which allows the user to digitize at a scale of 1:6,000 with a 1-acre MMU. The Habitat Digitizer allows the user to change the scale of mapping and the size of the MMU. Generally, feature detection of seafloor habitats was possible from the shoreline to water depths of approximately 30 meters, depending on water clarity.

In order to optimize the satellite imagery for visual interpretation, a number of processing steps were implemented to enhance the geopositioning and clarity of the imagery. These steps include: orthorectification to remove spatial distortions in the imagery due to relief displacement; pansharpening; deglinting; generating normalized reflectance values and, if possible, correcting for water column attenuation.

Several high-resolution satellite sensors currently orbit the earth and are capable of collecting detailed imagery. NOAA has used the Quickbird II satellite and the IKONOS satellite to provide imagery for benthic habitat mapping. Both the Quickbird II and IKONOS satellites provide commercially available panchromatic (black and white) and multispectral (blue/green/red/near-infrared) imagery. IKONOS panchromatic imagery has a 1 sq m panchromatic pixel dimension (meaning features larger then 1 m can be detected in the imagery) and a 4 m multispectral pixel dimension (meaning features larger then 16 sq m can be seen in the imagery). The Quickbird II panchromatic imagery has a 0.5 sq m panchromatic pixel dimension (meaning features larger then 0.5 m can be detected in the imagery) and a 2.8 m multispectral pixel dimension (meaning features larger then 8 sq m can be seen in the imagery).

Landsat satellite imagery, with a 28.8 m (~812 sq m) multispectral pixel and 14.25 m (~203 sq m panchromatic) pixel size, has also been used to characterize shallow-water benthic habitats. Several mapping projects in the Florida Keys have looked at changes in the extent and distribution of benthic habitats over time using Landsat imagery. These studies demonstrate that, when analyses of changes over time are needed and very detailed maps are not required, Landsat satellite imagery may be ideal.

Table 7. Estimates for gathering, processing, and developing benthic habitat maps from satellite imagery. Also included are estimated costs associated with assessing the accuracy of the benthic habitat maps. The estimates are based on a study area of 13,000 sq km and a 4,047 sq m (1 acre) Minimum Mapping Unit. The cost values presented could overestimate or underestimate actual costs by 25 percent or more.

imagery source	range of acquisition costs	average acquisition cost	estimated cost to produce map	estimated cost
Landsat	$00.41/sq km	$00.41/sq km	$285/sq km	$3,710,000
IKONOS	$35-150/sq km	$50/sq km	$285/sq km	$4,355,000
Quickbird II	$40-100/sq km	$50/sq km	$285/sq km	$4,355,000

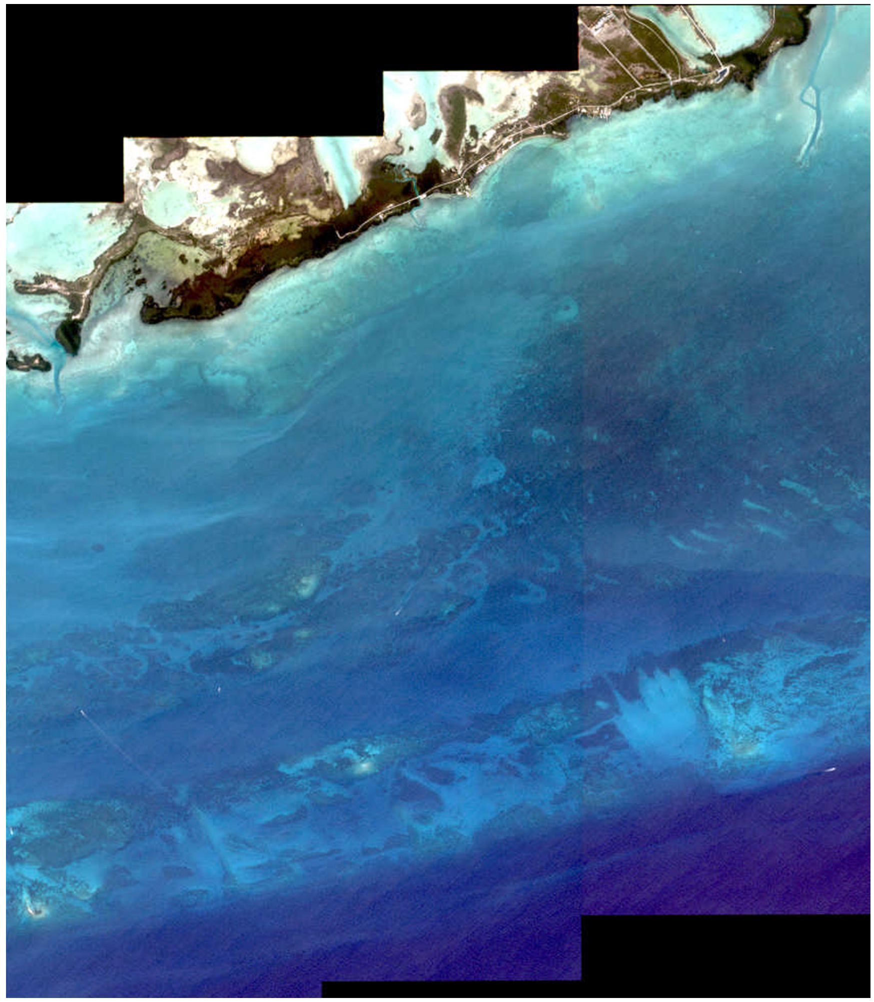
These estimates include some, but not all, imagery gathering and processing costs. Costs associated with conducting accuracy assessment assume a 4,047 sq m MMU and a 13,000 sq km area to be mapped. Map production and accuracy assessment costs are based on a cost estimate provided by Analytical Laboratories of Hawaii using IKONOS satellite imagery to produce a benthic habitat map for a portion of the Republic of Palau. Map production and accuracy assessment costs using Landsat imagery probably are less than the cost of using IKONOS imagery. Also, some reduction in map production and accuracy assessment cost may be expected when working in southern Florida rather than in Palau.

The IKONOS imagery is purchased in 11 km wide swaths, while the Quickbird II imagery is purchased in 100 sq km blocks. The imagery can be mosaicked together to produce complete images of locales. High-resolution satellite imagery provides precise and robust data with spectral and spatial resolution suitable for shallow water benthic mapping. Furthermore, both moderate-resolution Landsat and high-resolution satellite (e.g., Quickbird II) imagery provides efficient and effective global coverage for repeated imaging of remote islands that are often obscured by cloud cover. Furthermore, Landsat imagery is available for some areas as far back as 1985, making it an important resource for analyzing change over time.

Orthorectification

During orthorectification, digital imagery is processed using algorithms that eliminate each source of spatial distortion. The result is a georeferenced digital mosaic of several imagery scenes with uniform scale throughout the mosaic. After an orthorectified mosaic is created, visual interpreters can accurately and reliably delineate the boundaries of features in the imagery as they appear on the computer monitor using a software interface such as the NOAA Habitat Digitizer. Through this process, natural resources managers and researchers are provided with spatially accurate maps of habitats and other features visible in the imagery.

Mosaicking the Imagery


An IKONOS satellite image of a portion of the Florida Keys, Florida.

Georeferencing/mosaicking of the imagery is performed using several image analysis software programs, such as PCI OrthoEngine or Erdas OrthoBase. Dependng on which satellite is used, the imagery is initially orthorectified using the RPCs, then further orthorectified with supplemental GPS ground control and corrected for terrain displacement using the Digital Elevation Model data where available. When multiple scenes are available for a given locale, these scenes are collectively incorporated into the orthomosaic using mathematical bundle adjustments. Each scene is exported as a separate orthorectified file for further image processing. In addition, the best portions of each scene are selected for creation of the final "cloud-free" mosaic. Portions of each scene are selected to minimize sun glint, cloud interference, turbidity, etc. in the final mosaic. Where possible, parts of images obscured by sun glint or clouds are replaced with cloud/glint free parts of overlapping images. As a result, most mosaics have few or no clouds or sun glint obscuring bottom features. However, in some cases, clouds, sun glint, or turbid areas cannot be replaced with overlapping imagery. In these areas, such obstructions are minimized, but cannot be eliminated completely, resulting in unmapped areas.

Ground Control Points (GCPs) for Georeferencing

Fixed ground features visible in the imagery are selected for ground control points (GCPs), which are then used to georeference the imagery (i.e., link the image pixels to a real world coordinate system such as Universal Transverse Mercator). NOAA's National Geodetic Survey (NGS), the U.S. Geological Survey, and other organizations gather ground control data. Typically, GCPs are collected to ensure horizontal accuracy to within 5 cm of their location on the earth. Once GCPs are measured, they can be differentially corrected to the closest Continuously Operating Reference System (CORS) location, which further assures their positional accuracy.

GCPs need to be obtained for a wide distribution of locations points throughout the imagery whenever possible, since this results in the most accurate registration throughout each image. Only ground control points for terrestrial features can be collected and used. Because of positional distortion caused by the water column and the difficulty in obtaining precise positions for submerged features, GCPs in the water cannot be used to position imagery.

Image-to-Image Tie-Points

Image to image tie-points (distinct features visible in overlap areas of each frame such as street intersections, piers, coral heads, reef edges, and bridges) are then used to further co-register the imagery, especially for photos taken over open water where ground control points are not available. Softcopy photogrammetry software has the ability to automatically find such features common to overlapping imagery, but this automated function has mixed results for submerged features.

Image Analysis

Several intermediate, derived products are produced as the satellite imagery is processed for use in producing the benthic habitat maps. First, the raw satellite images are converted from Digital Numbers (DNs) to normalized reflectance. Normalized reflectance (or at-satellite reflectance) converts DNs into standardized, satellite-independent, comparable values. First developed for Landsat satellite imagery, the algorithm used to perform this conversion was modified for IKONOS image processing. As part of the conversion from DNs to at-satellite reflectance, the following equation is used (Green et al., 2000).

*R = pi * L/ (Eo cos(theta0) 1/r 2)*

L = radiance (from calibration provided by Space Imaging)
r = earth-sun distance in Astronomical Units
theta0 = the solar zenith angle
Eo = the mean solar exo-atmospheric irradiance in each band. (A convolution of the spectral response and solar radiation from Neckel and Labs (1984) was used to get Eo.)

The acquisition angles (ephemeris data) of the satellite relative to the ground at the time of image acquisition are also used to position the imagery. Calibration coefficients for the satellite are used to calculate at-satellite radiance, which is then transformed to reflectance. The normalized reflectance imagery is then transformed into water reflectance (or the signal <10 cm above the water surface). Water reflectance uses the near-infrared band to remove radiance attributed to atmospheric and surface effects (Stumpf et al., 2003). Water reflectance estimates how the signal (photons) received by the satellite is diminished as it passes through the atmosphere on the way down to the water-atmosphere boundary and on the way back up to the satellite after the signal leaves the water-atmosphere boundary. Water reflectance also estimates how the signal at the satellite is diminished by water vapor, clouds, specular effects at the water surface (wave surface glint), and other signal-absorbing and diffusing materials.

Finalizing the Process

Final mosaics are created in "img" file format (georeferenced image file) with a Universal Transverse Mercator (UTM), projection, North American Datum of 1983 (NAD83). These mosaics are color-balanced in order to provide the most seamless, cloud-free product available for creating benthic habitat maps.

Digitizing Benthic Habitats

The following procedures are relevant to benthic habitat mapping regardless of the where the imagery or other source data (e.g., multibeam data) comes from. Some steps described in these procedures may require modification, depending on the type of digital data being used.

Individual georeferenced mosaics are loaded into ArcView with the NOAA Habitat Digitizer and Image Analysis extensions activated. ArcView's Image Analysis extension allows each image to be easily manipulated to optimally adjust contrast, brightness, and color. The user sets the MMU in the Habitat Digitizer extension. As discussed previously, the MMU is set based on the source of the imagery, the scale of the maps desired, the costs of completing the maps, and the objectives of the mapping project. Depending on what the MMU is set to, some features visible in the imagery, such as small isolated patch reefs and sea walls that, while important features, are quite small and beyond the scope of this mapping project.

An aerial photograph of Fort Jefferson, Florida Keys, Florida.

Digitizing scale is typically set to 1:6,000 in the Habitat Digitizer. Experimentation indicated that digitizing at this scale optimizes the trade-off between positional accuracy of lines and time spent digitizing. In general, line placement conducted while zoomed in at large scales results in excellent line accuracy and detail but can be quite time consuming. Conversely, while zoomed out, lines can be drawn quickly but lack both detail and positional accuracy.

Determining the Optimum Digitizing Scale

Results of an experiment conducted during benthic habitat mapping of the Caribbean were used to determine the optimum digitizing scale to maximize accuracy and minimize map production time. In the Caribbean digitizing experiment a 25 acre area composed of a variety of habitat types was mapped at 1:1,500, 1:3,000, 1:6,000, and 1:12,000 on-screen scale (scale that the image appears on the computer monitor). Five replicates were conducted at each scale. Each trial was timed so we could evaluate the influence of mapping scale on production time. Resulting maps were evaluated for deviations in polygon detail relative to the map digitized at a 1:1,500 scale. At 1:1,500, individual pixels are clearly discernible allowing highly detailed and accurate maps to be created by closely following the contours of even the most convoluted habitat boundary. Additional increases in zoom do not result in an increase in map detail and accuracy since individual pixels are already visible at 1:1,500. Therefore, the map created at a 1:1,500 scale was used as a reference against which to compare maps digitized at scales of 1:3,000, 1:6,000, and 1:12,000.

The results of this experiment indicated that there is no appreciable loss in polygon detail and accuracy by digitizing at 1:6,000 while mapping time was dramatically reduced. Therefore all polygons were digitized at this scale except when subtle habitat boundaries were not easily discernible at 1:6,000 and zooming out to a more broad scale was required to place boundaries correctly. In this case, digitizing generally took place at a scale of approximately 1:10,000.

Visual Interpretation

Using the Habitat Digitizer, habitat boundaries are delineated around seafloor benthic habitat feature signatures (e.g., areas with specific color and texture patterns) in the orthorectified mosaic corresponding to habitat types in the Classification Scheme. This is often accomplished by, first, digitizing a large boundary polygon such as the habitats that compose the shoreline and then appending new polygons to the initial polygon or splitting out smaller polygons within. Each new polygon is attributed with the appropriate habitat designation according to the classification scheme. It is believed that the positional accuracy of polygon boundaries is similar to that of the mosaics since delineation is performed directly on the digital imagery. Brightness, contrast, and occasionally color balance of the mosaic are manipulated with Image Analysis to enhance the interpretability of some subtle features and boundaries. This is particularly helpful in deeper water, where differences in color and texture between adjacent features tend to be subtle and boundaries can be more difficult to detect. Particular caution is used when interpretation is performed from altered images, since results from color and brightness manipulations can sometimes be misleading.

The visual interpreter is typically provided with a series of imagery files to aid in delineating and attributing polygons. In the case of IKONOS imagery, these include the unmodified multispectral scenes (4 m pixel imagery), normalized reflectance scenes (4 m pixel imagery), and pansharpened, multispectral scenes (1 m pixel imagery). Additional collateral information, including previously completed habitat maps, NOS nautical charts, LIDAR data, and other descriptive references dealing with benthic and coastal habitats of the area, are used to assist with image interpretation.

Optical Observation Imagery

Once collected, the bathymetric and imagery data can be used, in combination with optical validation data—actual imagery—of the seafloor, to derive benthic habitat maps. Direct observations and optical technologies are generally used to observe and collect validation data—imagery—of the seafloor. Remotely operated vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), manned submersibles, Laser Line Scanning (LLS) technologies, drop cameras, as well as SCUBA divers can collect imagery of the seafloor. SCUBA divers are generally limited to collecting imagery in shallow water (less than 15 fm). ROVs, AUVs, drop cameras, LLSs, and manned submersibles are able to collect imagery in both shallow and deep water. The challenge is to determine how many observations are needed in order to adequately characterize a region of the seafloor. When the seafloor is relatively homogeneous, fewer images may be needed. A complex seafloor, with outcrops or high rugosity, may require many observations for adequate characterization.

A thorough evaluation of available bathymetry data should be conducted as part of a mission to acquire seafloor optical observation imagery. The evaluation can help establish priority areas and improve efficiency. In addition, every effort should be made to piggyback—use ships of opportunity—on other survey missions.

The costs of acquiring optical observation data vary widely. A ship equipped with an ROV or manned submersible may cost as much as $30,000/day. Safe and efficient operation of these vehicles is contingent on having accurate, detailed bathymetric data. Prioritization of areas to be surveyed also is important. Simple drop cameras or ROVs are much less expensive (~$50,000/system), can readily be used down to ~1000+ m, and are easily deployed from a variety of vessels. Diver observations and photographs are inexpensive and the most common source of validation data in depths down to ~15 fm, but are depth and in-the-water time limited and can be dangerous, particularly in remote areas where no diver facilities, such as hyperbaric chambers, are available.

Ground Validation

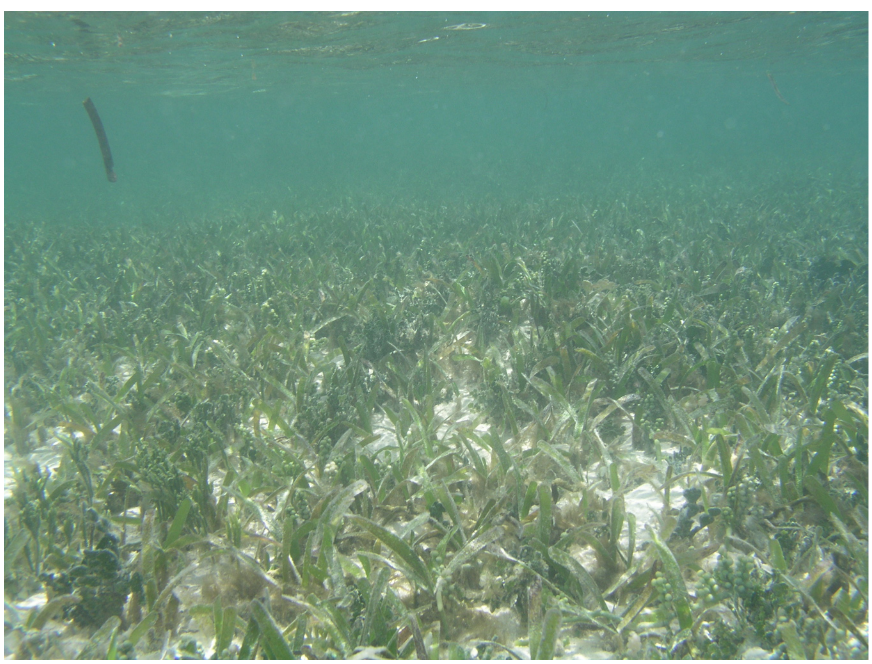
Following careful evaluation of the source data (e.g., satellite imagery), and in some cases creation of a "first draft" habitat map through the process outlined in the previous section, selected field sites are visited in the field for typological validation. Selection of field sites where this validation occurs includes: areas in the data with confusing or difficult to interpret signatures; transects across many representative habitat types occurring in different depths and water conditions; a survey of the zones; and confirmation of preliminary habitat delineations if a first draft was produced.

Navigating to field sites is accomplished in a variety of ways including uploading position coordinates from the mosaic into an onboard GPS and navigating to those waypoints using an onboard PC connected to GPS allowing navigation using digital nautical charts or the mosaic and actual visual navigation using landmarks visible in the imagery.

Whenever possible, field activities are conducted in partnership with local experts. Available data (e.g., satellite imagery) and, when available, draft benthic delineations are used in the field to facilitate comparison of feature signatures in the data to actual habitats at each site. Individual sites are visually evaluated by snorkeling and free diving or directly from the boat in shallow, clear water. Habitat transitions are evaluated by swimming transects across habitat types to further guide placement of polygon boundaries.

Habitat type(s), zone, approximate depth, position (GPS), image number, and other descriptive information are recorded at each site. Field data for each site are then compiled into a text table with a latitude/longitude field to allow overlay of the field information on the mosaic and habitat polygons. These data are used as *Ground Validation Points*. Where depth and water clarity permit, satellite imagery is used to navigate across multiple bottom features allowing continuous confirmation of habitat types and transitions between each site.

Once the field data are collected and processed, polygon boundaries and habitat classifications are created or revised where necessary on the draft map, and zone attributes are assigned to each polygon using the Habitat Digitizer. This draft of the habitat maps is then reviewed and revised with the guidance of a panel of local experts at peer review sessions held at several locations throughout the region and over the Internet. Review session participants typically include members of the local research and management community.



During these peer review sessions, particular attention is given to polygons labeled as "unknown" and areas not visited during ground truth activities. Revisions based on comments from local experts are then completed and final habitat maps are produced. Thematic accuracy is then assessed for these final maps.

Accuracy Assessment

The thematic accuracy of the habitat information depicted on the map—and derived from source data, such as directly observed or remotely sensed data—is determined by the quantitative process of accuracy assessment. The purpose of accuracy assessment is to identify and quantify errors in the maps by comparing the attributes of the map to reference data at various sites. It is important that the mapmaker know how reliably a given habitat can be classified. This parameter is called "producers accuracy." The users of a map product want to know the percentage of the polygons of a particular class or habitat type that are correctly attributed. This parameter is called "users accuracy." Furthermore, the source data that may be suitable for mapping coral reef habitats can be acquired from a wide variety of platforms and imaging systems, each having it's own strengths and weaknesses. It is important to identify the technical merits of each imaging platform, one measure of which is the thematic accuracy of the map products.

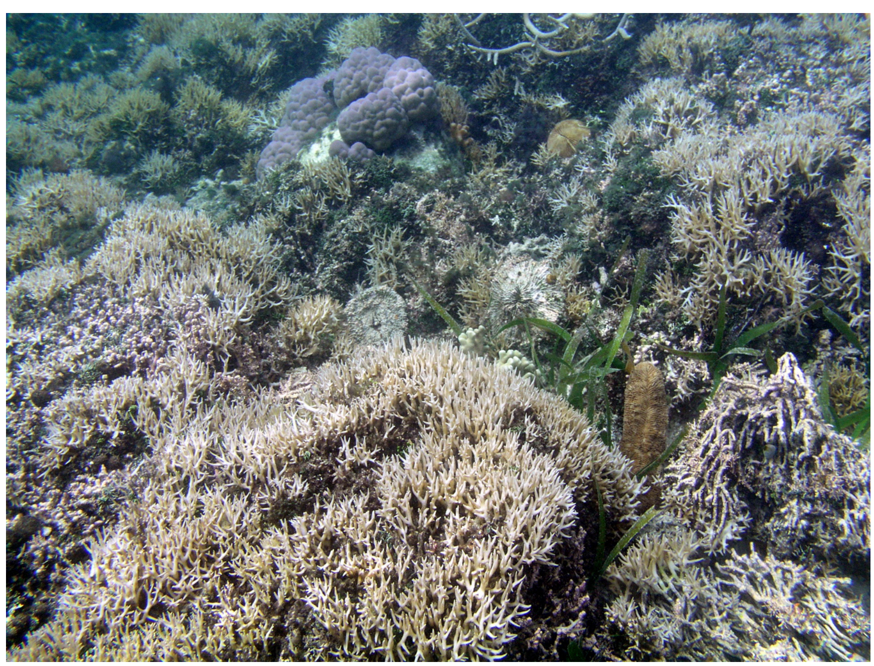
To determine the overall accuracy of the mapped product, GIS data prepared by visually interpreting satellite imagery or other digital data is assessed for accuracy using conventional methodologies. Specific areas being mapped are used as test areas for the mapping effort. A statistically robust data set composed of random field habitat observations is collected within the test areas to assess the accuracy of the mapped product. These areas are chosen based on input from the local marine biologists and coral reef managers. These groups provide advice on the location of the most diverse benthic communities and also areas of particular importance, based on management strategies and marine protected areas. The goal of this team is to collect accuracy assessment field data representing as many of the habitats that occur in the region as possible.

The thematic accuracy of all mapped products is determined at both the most general and the detailed levels of the classification scheme, including both the biological cover type and geomorphological structure. A representative number of coral ecosystem test areas are selected based on the diversity of the habitat types and to assure that all benthic habitats throughout the study area are represented. The accuracy of the map of the test area(s) is, therefore, considered a conservative representation of the thematic accuracy of the habitat maps prepared for the entire area.

An accuracy assessment process is designed and executed to quantify the thematic accuracy of the maps generated at all levels of the classification scheme. Statistical analysis methods are applied that have been developed by other researchers (Hudson and Ramm, 1987; Congalton, 1991; Rosenfield et al., 1982). Typically, for mapping coral ecosystem test areas in southern Florida, 20 to 30 field habitat observations are completed per detailed structure as well as detailed biological cover type. The accuracy assessment results are reported using an error matrix that compares the attribute assigned to a polygon that is generated from the interpretation of the source data with that of the determination from field observation. For an area as large and as diverse as southern Florida, input from local experts will be critical to identify the test areas where accuracy assessment will occur.

Benthic habitat maps of these test areas are generated from the source data (satellite imagery or other digital data). All image interpretation and digitizing is conducted by personnel with particular expertise in the location and characteristics of southern Florida's benthic habitats. The field habitat characterization data collection methods for thematic accuracy assessment differed little from the data collected for ground validation. The primary distinction between the two data sets is the method of selection of the field points. Where as the assessment sites for ground validation are selected to specifically investigate habitat types and gradients of spectral signatures in the imagery, a random stratified sampling method is implemented to select field sites to test map accuracy (Congalton, 1991).

Subsequent to completion of the second draft coral reef habitat maps, waypoints are generated using a stratified random sampling scheme. Twenty to thirty accuracy assessment waypoints are collected per test area for each detailed structure and detailed cover class encountered. Waypoint files are generated from these points and all waypoints that can be safely accessed are navigated to using a portable GPS unit. Upon arriving at the waypoint, a weighted meter line is dropped, a buoy fastened and site and habitat specific data collection is undertaken. After deployment of the buoy, 100 GPS positions are collected at one-second intervals and are averaged to generate a single position for the sampling site, or waypoint.



Three benthic habitat assessments are conducted at each waypoint. A point assessment is conducted by surveying the one square meter area around the point where the weight dropped. Two area assessments are conducted in an area within a seven-meter radius around the weight. The first assessment identifies the most common habitat type within the area and the second identifies the second most common habitat type within the area. The depth of the site is recorded using a hand held depth sounder. Benthic habitat assessments are made using a glass bottom look box, free diving, or observing from the surface. All diving is conducted by breath holding or snorkeling on the surface. In areas where waves and sea conditions are prohibitive to safely accessing the waypoint by boat, the GPS is placed in a watertight box and swam to the survey point.

Data, including, but not limited to, site ID, depth, most common habitat, zone and assessment method are recorded for each waypoint using the GPS data logger equipped with a custom data dictionary designed to meet the specifications of the Coral Reef Habitat Classification Scheme. At the end of each field day, the data in the GPS data logger are downloaded, differentially corrected to the closest CORS station and seamlessly converted to ArcView GIS format. All hand written descriptions for each waypoint are entered in waterproof notebooks and transferred to the GIS by hand. The total number of benthic habitat characterization waypoints collected is dependent on the size of the MMU, the source of the digital data used as the basis for mapping, and the complexity of the ecosystem as defined by the Classification Scheme.

To maintain objectivity in the analysis of accuracy, an independent team should conduct this work. For example, the Coral Reef Assessment and Monitoring Program (CRAMP) biologists from the Hawaii Institute of Marine Biology from the University of Hawaii at Manoa conducted the accuracy assessment of NOAA's recently completed benthic habitat maps of American Samoa, Guam, and the Northern Marianas. The accuracy assessment point theme and the benthic habitat polygon themes are overlaid on the source data (e.g., satellite imagery) in the GIS. The GIS is used to identify and select all points within the polygons that matched the polygon habitat type. These are set aside as correct calls. The mismatched pairs are closely examined to determine how and why the accuracy assessment points do not match the habitat polygons.

The classification errors that occur between the MMU and size of accuracy assessment areas are accounted for in this analysis. A map classification is not considered incorrect in a case where a seven-meter radius field assessment falls on a habitat feature in the field that is smaller than the MMU. For example, if a field assessment falls on a small patch reef surrounded by sand that is less than the MMU and thus is not mapped, the point is excluded from the accuracy assessment report. Points that fall close to polygon boundaries are all included as it is assumed that the probability of error contributing to false negatives is equal to that for false positives. The habitat type for the portions of the test area that is not interpretable due to cloud cover, glint or water quality is classified as "unknown." The accuracy assessment points that fall within polygons with the habitat type of "unknown" are not included in the accuracy analysis.

Data Processing and Habitat Mapping

Collection of bathymetric, imagery, and optical validation data represents a significant commitment of resources and funds. However, data collection alone does not ensure that benthic habitat maps are produced. A significant commitment of resources and funds also is required to process bathymetry, imagery, and optical validation data and to synthesize these data with the critical biological information (Table 7). The resulting maps are needed to create the complete picture of an ecosystem in order to describe and determine EFH and HAPC. A complete assessment of the cost to process the bathymetric and imagery data, incorporate the validation data, and develop maps suitable for EFH and HAPC characterization and implementation needs to be completed.

Key Trade-offs

Mapping the shallow-water (~0-40 m) benthic habitats of southern Florida will require some technologic, geographic, and other compromises to be made. It is unlikely that sufficient funding will be available for the sustained period of time needed to comprehensively map all of southern Florida's shallow-water coral ecosystems. As a result, priorities will need to be established and tradeoffs made. Below are descriptions of some of the tradeoffs that will be considered and how choices about various aspects of benthic habitat mapping, such as sources of data, the size of the geographic to be mapped, the size of the MMU, and the thematic accuracy of the map products affect these tradeoffs.

Source of Data

The cost of acquiring, processing, georeferencing, and mosaicking the imagery used to generate the benthic habitat map varies considerably depending on the source of the imagery. Aerial photography is relatively inexpensive to collect per unit area, but is relatively expensive to georeference (ortho-rectify) and mosaic together in order to generate a map. High-resolution satellite imagery is more expensive to collect per unit area but is less expensive to georeference and mosaic. Digital camera imagery from aircraft also is relatively inexpensive to collect. The cost to georeference and mosaic the imagery tends to fall between those of aerial photography and high-resolution satellite imagery. In areas where traditional remote sensing cannot adequately map the area (for example, in areas with consistent turbidity or deep depth), active sensors such as sonars and LIDAR could be used, but have high associated costs.

Minimum Mapping Unit size

The size of the Minimum Mapping Unit (MMU) can dramatically affect the time required to produce a benthic habitat map of a given area and, as a result, can dramatically affect the cost of producing a benthic habitat map of a given area. Also, the type of technology (e.g., LIDAR) that provides the imagery from which the map is generated may have limits on the size of MMU that it can support. Finally, the amount of optical observation information needed to validate the accuracy of the map is directly dependent on the size of the MMU.

Area to be Mapped

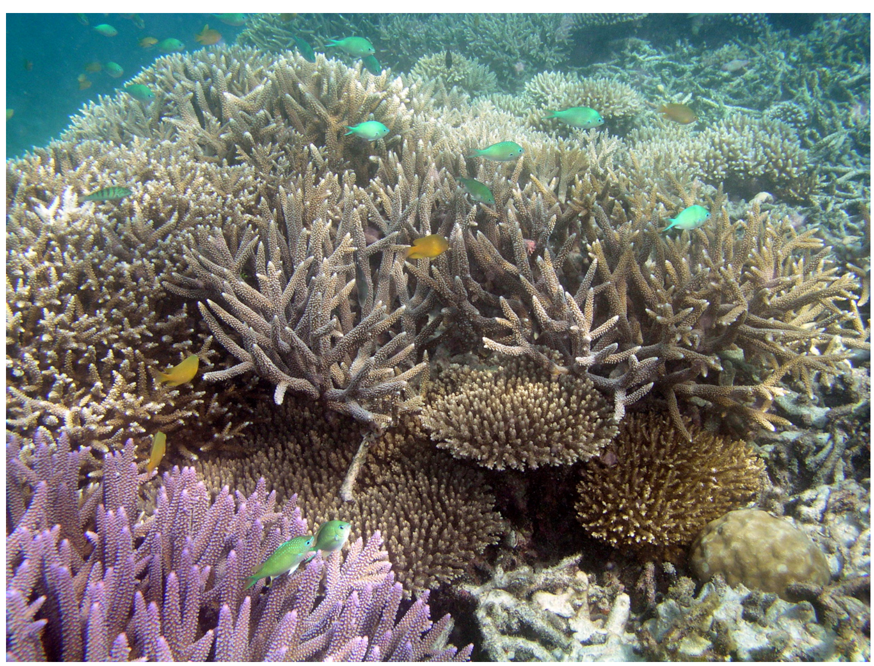
As discussed above, the size of the area to be mapped directly affects the level of effort required to acquire imagery, the size of the MMU, and the amount of optical observation information needed, and each of these factors affects the overall cost of producing benthic habitat maps.

Number of Habitat Types

The number of benthic habitat categories—i.e., coral ecosystem complexity—that are classified during the process of generating a map directly affects map production cost. The greater the number of habitat categories defined, the greater the cost of identifying, mapping, and validating the resulting map. Also, the greater the number of benthic habitat categories, the higher the resolution of the imagery required to identify and map the different habitats. Finally, the higher the number of habitat categories mapped, the greater the number of optical observations required to validate the accuracy of the map product.

Thematic Accuracy

Independently evaluating the thematic accuracy of a map of shallow-water benthic habitats is one of the most important aspects of the mapping process. The consensus position among potential users of southern Florida benthic habitat maps is that higher thematic accuracy—at the expense of a smaller MMU—is preferred. The preferred accuracy is 90-95 percent thematic accuracy for major categories of habitat. The collection of optical observations to statistically test the accuracy of a map is directly related to required map accuracy: the higher the required accuracy required, the greater the number of optical observations required to analyze accuracy.



Classification Schemes

A classification scheme for categorizing the various habitat types that will be encountered in South Florida will be developed through inter-agency participation. State, local and other federal agencies, as well as local groups representing fishers, divers, etc. will be invited to participate in classification scheme development workshops. NOAA has successfully directed the development of classification schemes for Puerto Rico and the Virgin Islands (Kendall et al., 2003) and the main Hawaiian Islands (Coyne et al., 2001), through consensus-building workshops. The classification scheme for mapping southern Florida's shallow-water benthic habitats also will be developed through a consensus building process.

SCHEME

The Florida Fish and Wildlife Conservation Commission recently developed a hierarchical System for Classification of Habitats in Estuarine and Marine Environments for Florida (SCHEME; Madley et al., 2002) that contains coral habitat categories that will be available for review and modification during the workshop process. Also, the National Coral Reef Institute at Nova Southeastern University has been working toward completion of coral habitat maps for Broward County, FL using data mostly derived from LIDAR and acoustic sensors. Their work will be helpful with developing a classification system for South Florida that accounts for resolution available from LIDAR and acoustic sensors in deeper water. The classification system for South Florida will need to include deeper water habitats that will be mapped with acoustic data as well as the shallow water habitats that can be mapped with optical imagery. Thus, workshops intended for developing a classification system will also involve a decision process toward remote sensing techniques, tools, and interagency coordination for acquiring the habitat data and accuracy assessments needed for the final products.

The SCHEME classification scheme can be downloaded as a PDF from the following URL: http://research.myfwc.com/features/view_article.asp?id=24987

NOAA Classification Scheme

A hierarchical classification scheme was created to define and delineate shallow-water benthic habitats. The classification scheme was influenced by many factors including: requests from the management community, NOS's coral reef mapping experience in the Florida Keys and Caribbean, existing classification schemes for the Pacific and Hawaiian Islands (Holthus and Maragos, 1995; Gulko, 1998; Allee et al., 2000), other coral reef systems (Kruer, 1995; Reid and Kruer, 1998; Lindeman et al., 1998; Sheppard et al., 1998; Vierros, 1997; Chauvaud et al., 1998; Mumby et al., 1998; Kendall et al., 2001), quantitative habitat data for the U.S. Pacific Territories, the minimum mapping unit (MMU - 1 acre for visual imagery interpretation), and analysis of the spatial and spectral limitations of satellite IKONOS imagery.

The hierarchical scheme allows users to expand or collapse the thematic detail of the resulting map to suit their needs. This is an important aspect of the scheme as it will provide a "common language" to compare and contrast digital maps developed from complementary remote sensing platforms. Furthermore, it is encouraged that additional hierarchical categories be added in the resulting geographic information system by users with more detailed knowledge or data for specific areas. For example, habitat polygons smaller than the MMU can be delineated, such as reef holes found in parts of a marine region, or habitat polygons delineated as colonized pavement using this scheme could be further attributed with health information (i.e., bleached, percent live cover) or species composition (i.e., Porites, Montipora).

The hierarchical scheme was prepared through consultation, meetings, and workshops that included key coral reef biologists, mapping experts, and professionals throughout the Pacific territories. Modifications were made throughout the development process based upon feedback provided by workshop participants and other contributors. Additional modifications were made during the mapping process to ensure that each category definition reflected the intended habitats and zones encountered in the field as accurately as possible. For instance, the separation of biological cover and geomorphological structure in the present scheme represents a significant evolution of previous versions of the classification schemes developed for mapping of the Florida and the U.S. Caribbean.

Classification Scheme Description

The classification scheme defines benthic habitats on the basis of three attributes: large geographic "zones" which are comprised of smaller geomorphological structure and biological cover of the reef system. Every polygon on the benthic community map will be assigned a structure and cover within a zone (i.e., uncolonized sand in the lagoon, or coral on aggregate reef on the bank). Biological cover and geomorphological structure are further defined by three density classes. "Zone" indicates polygon location, "biological cover" indicates the predominant biological component colonizing the surface of the feature, and "geomorphological structure" indicates the physical structural composition of the feature. The description of each cover and structure includes an example image. The zone descriptions include schematic descriptions. The hierarchical scheme was prepared through consultation, meetings, and workshops that included key coral reef biologists, mapping experts, and professionals throughout the island territories. The separation of biological cover and geomorphological structure in the present scheme represents a significant evolution of previous versions of the classification schemes developed for mapping of the Caribbean and Hawaiian Islands. For more detailed descriptions of this classification scheme, please visit: http://biogeo.nos.noaa.gov/products/us_pac_terr/methods..htm.gov

Next Steps

This MIP has been reviewed by both the Florida Mapping Steering Committee and the other agency representatives identified in Appendix 1. The final MIP is available as a PDF on http://biogeo.nos.noaa.gov

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Disclaimer

This MIP refers to certain commercial companies or products that either have been used by NOAA to produce mapping products or may have discussed mapping activities with NOAA. Inclusion of these commercial company names or products does not indicate or imply any endorsement of any commercial company or product by NOAA.

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Table 1. Summary of past, current, and future mapping activities in the south Florida region.

Mapping Activity	Mapping Organization	Completion Date	Geographic Area	Point of Contact	Data Source	Comments
Seagrass Characterization	Florida International University	ongoing	Florida Keys/West Florida Shelf	Jim Fourqurean (Jim.Fourqurean@fiu.edu)	in-situ characterization	Over 300 site-specific seagrass characterizations. Includes GPS coordinates and other field data.
Coral Reef and Hard-bottom Community Composition	FWRI	ongoing	Florida Keys / Southeastern Florida	Carl Beaver (Carl.Beaver@MyFWC.com)	in-situ characterization, video transects	Data for 43 sites (Florida Keys)
Seagrass mapping	FWRI	ongoing	Biscayne Bay	Kevin Madley (Kevin.Madley@MyFWC.com)	aerial digital imagery	Visual interpretation of imagery
Seagrass Mapping	FWRI	ongoing	Western Everglades	Kevin Madley (Kevin.Madley@MyFWC.com)	aerial digital imagery	visual interpretation of imagery
ArcIMS Map Server	FWRI	ongoing	focus on Southeast-South portion of Florida	Kathleen O'Keife (Kathleen.OKeife@MyFWC.com)	various	Repository for available map data to support FWRI and state monitoring, management, and conservation goals.
West Florida Shelf seafloor map	FWRI	complete	a portion of the West Florida Shelf from Sarasota Bay to Cape Romano	FWRI (on-line)	NOAA bathymetric fishing charts at a 1:100,000 scale	A map of about 7,800 sq km of seafloor. The GIS data represent bottom type of the southwest coast of Florida. Data were digitized from charts. Bottom types represented are: Sand, Gravel, Rock, Shell, Mud, and Coral.
Benthic Habitats of the Florida Keys	FWRI/NOAA	1998	primarily Florida Keys	Henry Norris (Henry.Norris@MyFWC.com)	aerial photography	Used visual interpretation to identify seafloor features. Large areas unmappable. MMU generally > 4000 sq m.
Data Collection for portions of Florida Keys	NASA/USGS	ongoing	focus on Biscayne Bay, northern Florida Keys, and Dry Tortugas	John Brock, USGS (jbrock@usgs.gov); Wayne Wright, NASA, Matt Patterson, NPS	EAARL LIDAR	technology acquires LIDAR with backscatter and digital camera imagery simultaneously.
Benthic Habitat Mapping of Broward County reefs	NSUOC, NCRI, and FWRI	complete	Broward County, FL	Bernhard Riegl (rieglb@nova.edu)	LADS LIDAR, single beam acoustic survey, and aerial photography	Comparing technologies, including backscatter, to map benthic habitats. Collected numerous site specific field data to produce and validate benthic habitat maps (Riegl and Purkis, 2005).

Benthic Habitat Mapping of Palm Beach County reefs	NSUOC, NCRI, and FWRI	ongoing	Palm Beach County, FL	Bernhard Riegl (rieglb@nova.edu)	LADS LIDAR, single beam acoustic survey, aerial photography	Comparing technologies, including backscatter, to map benthic habitats. Collected numerous site specific field data to produce and validate benthic habitat maps (Riegl and Purkis, 2005).
Benthic Habitat Mapping of Miami-Dade County reefs	NSUOC, NCRI, and FWRI	TBD	Miami-Dade County, FL	Bernhard Riegl (rieglb@nova.edu)	LADS LIDAR, single beam acoustic survey, aerial photography	Comparing technologies, including backscatter, to map benthic habitats. Collected numerous site specific field data to produce and validate benthic habitat maps (Riegl and Purkis, 2005).
Nearshore Reef Mapping of Palm Beach County reefs	Palm Beach County government	ongoing	Palm Beach County, FL	Janet Phipps (JPHIPPS@co.palm-beach.fl.us)	multiple projects to digitize nearshore reefs of Palm Beach County	
Benthic Habitat Mapping of St. Lucie Inlet reefs	NSUOC, NCRI, and FWRI	ongoing	Martin County, FL	Jeff Beal (Jeff.Beal@MyFWC.com)	LADS LIDAR, single beam acoustic survey, aerial photography	
Seagrass mapping	FWRI	ongoing	Florida Bay	Kevin Madley (Kevin.Madley@MyFWC.com)	aerial natural color photography	visual interpretation of imagery
Fisheries Habitat Characterization	NMFS	ongoing	portions of West Florida Shelf (Apalachacola to Tampa along 73 m depth range)	Andy David (Andy.David@noaa.gov)	multibeam sonar	Acquired acoustic backscatter during collection. Used drop camera and ROV to collect biologic field data. Has not developed benthic habitat map using data. Interested in offshore fisheries, esp. 60-80 m deep coral ecosystems and places like Pulley Ridge.
Dry Tortugas Reserve Characterization	NMFS and NOS	ongoing	Shallow-water reef/sand interface	Don Field, NMFS (Don.Field@noaa.gov)	IKONOS and Quickbird II satellite imagery and aerial photography	Has data on 30 permanent fish count stations for 2 years before and 4 years after designation.
Seagrass Surverys	NPS	ongoing	Biscayne Bay	Matt Patterson (Matt_Patterson@nps.gov)	TBD	
Geologic Surveys	NPS	ongoing	National Parks in southern Florida	Matt Patterson	TBD	
Oculina Bank Characterization	NURC	ongoing	Oculina Bank deep water coral ecosystems	TBD	multibeam sonar	
Coral Reef and Hard-bottom Community Composition	NURP/UNCW	ongoing	Florida Keys	Steve Miller (smiller@gate.net)	in-situ characterization	Data for more than 300 sites
Dry Tortugas Reserve Fisheries Utilization	Univ. of Miami	ongoing	Dry Tortugas	Jerry Ault (jault@rsmas.miami.edu)	used side scan and multibeam sonar data and diver survey data to improved existing maps.	produced detailed habitat maps with 200 X 200 m MMU. Spatially explicit links to fisheries use of habitat. Considers fishery ecoregion can extend to Tampa for certain species (e.g., hogfish).

Florida coast from shoreline to ~1km from shore over water	US ACE	2004	entire state	Jeff Lillycrop (Jeff.Lillycrop@sam.usace.army.mil)	SHOALS LIDAR	data will be provided to public through Coastal Services Center, NOS
Bathymetry Mapp of Southern Florida	USF	complete	Florida Keys region	Dave Palandro (palandro@seas.marine.usf.edu)	various sources	probably the best complete bathymetry map of region. Does not include West Florida Shelf.
Ecosystem Change Analysis of South Florida/Florida Keys	USF	complete	Florida Keys region	Dave Palandro	Landsat and IKONOS satellite imagery	Focus onn using spectral analysis to assess change in habitats over 18 year time period and map accuracy of change maps.
Dry Tortugas multibeam characterization	USF	complete	Dry Tortugas	Dave Naar, USF (naar@usf.edu)	multibeam sonar	Primary interest is in geology of area (and links to fisheries).
Florida Middle Grounds	USF	ongoing	Middle Grounds of Gulf of Mexico	Dave Naar	multibeam sonar	continuation of collaborative effort to complete acoustic data collection of Florida Middle Grounds
Maps showing Sedimentary and Biological Environments, Depth to Pleistocene Bedrock, and Holocene Sediment and Reef Thickness from Molasses Reef to Elbow Reef, Key Largo, South Florida	USGS	1997	Florida Keys	Barbara Lidz (blidz@usgs.gov)	aerial photography from 1975 and 1991; other sources	Lidz, et al., 1997. Maps extend from the Keys seaward to an upper-slope terrace in 40 m deep water. The benthic habital map was derived from visual interprettion.
Maps of Bedrock beneath Coral Reefs	USGS	2000	Florida Keys	Barbara Lidz	seismic geophysical data	Lidz, 1997.

Table 2. Summary of technologies used to provide imagery for coral ecosystem mapping.

Type of Technology	Technology subcategory	Ancillary Data	Swath Width	Feature identification capability	Caveats
Acoustic Sonar	launch or shallow draft ship-based shallow water (~0–400 m depth) bathymetry	acoustic backscatter	Swath width is depth dependent; ranges from 3X to 7X water depth	Backscatter data can be used with extensive field data to characterize seafloor features. May be possible to identify 3-5 categories of seafloor habitat.	Acoustic data with backscatter have not been used to synoptically maps benthic habitats. Any seafloor mapping would require extensive ground truthing data. Collection of ground truthing data logistically difficult. Many types of shallow-water sonars systems are available. Each has specifications (e.g., swath width) that vary. Extensive oceanograhic data collection required in order to calibrate sonar data for nautical charting uses.
	ship-based deep water (~>400 m) bathymetry	acoustic backscatter	Swath width is depth dependent; ranges from 3X to 7X water depth	Backscatter data generally poor in deeper water. May be possible to identify 3-5 categories of seafloor habitat.	Acoustic data with backscatter have not been used to synoptically maps benthic habitats. Any seafloor mapping would require extensive ground truthing data. Collection of ground truthing data logistically difficult. Many types of deep-water sonars systems are available. Each has specifications (e.g., swath width) that vary. Extensive oceanograhic data collection required in order to calibrate sonar data for nautical charting uses.
LIDAR	helicopter or fixed wing aircraft-based (~0–50 m) bathymetry	laser backscatter	Swath width is dependent on altitude of aircraft platform and LIDAR configuration.	Generally, can be used to identify 5-6 categories of features, including some types of habitat, in water 0-40 m deep.	LIDAR with backscatter has not been used to synoptically map large areas. Use for mapping affected by clouds, cloud shadows, and water quality, all of which limit penetration of laser into water column.
Photography	fixed wing aircraft-based digital or film camera (altitude 1000–>12,000 m)	none	Swath width (image footprint) is dependent on altitude of aircraft platform and camera configuration.	Multispectral (Red-Green-Blue-nearIR) digital camera and film imagery routinely used to map shallow-water coral ecosystems. Generally, can be used to identify as many as 35 benthic habitat features in water 0-30 m deep.	Photography has been used to synoptically map large areas. Use for mapping affected by clouds, cloud shadows, and water quality, all of which limit penetration of laser into water column.
Hyperspectral Imaging	fixed wing aircraft-based digital instrument (altitude 1000–>12,000 m)	10s of spectrally-discrete color bands	Swath width is dependent on altitude of aircraft platform and hyperspectral instrument configuration.	The numerous spectrally-discrete color bands can be used, with image analysis software, to identify unique benthic habitats based on their spectral signature. Generally, can be used to identify benthic habitat features in water 0-30 m deep.	Technology has not been used to synoptically map large geographic areas. Use for mapping affected by clouds, cloud shadows, and water quality, all of which limit penetration of laser into water column.
Satellite Imagery	high resolution (~<4 m pixel) satellite platform (~700 km orbit)	≤ 1 m panchromatic imagery	Swath width (image footprint) is ~ 11 km wide and several hundred km long	Multispectral (Red-Green-Blue-nearIR) imagery routinely used to map shallow-water coral ecosystems. Generally, can be used to identify as many as 35 benthic habitat features in water 0-30 m deep.	Satellite imagery has been used to synoptically map large geographic areas. The imagery is especially valuable for mapping remote areas. Use for mapping affected by clouds, cloud shadows, and water quality, all of which limit penetration of laser into water column.
	moderate resolution (~>28.5 m pixel) satellite platform (~700 km orbit)	14.25 m panchromatic imagery	Swath width (image footprint) is~170 km wide and 180 km long	Multispectral (Red-Green-Blue-nearIR) imagery routinely used to map shallow-water coral ecosystems. Generally, can be used to identify as many as 5–10 benthic habitat features in water 0-30 m deep.	Satellite imagery has been used to synoptically map large geographic areas. The imagery is especially valuable for mapping remote areas. Use for mapping affected by clouds, cloud shadows, and water quality, all of which limit penetration of laser into water column. Imagery is especially valuable for regional assessments and change analyses.

Appendix 1. List of participants involved in the development of the Southern Florida Shallow-water Coral Ecosystem Mapping Implementation Plan.

NOAA convened two meetings in Florida in November 2004 to gather information from organizations responsible for management and conservation of Florida's coral ecosystems. Participants in those meetings, as well as other discussions, are provided in this list. Names in Bold indicate members of the MIP development Steering Committee. List updated 5/18/05

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Appendix 2. A summary of mandated and other management, regulatory, or conservation requirements for the development of bathymetry and benthic habitat maps of southern Florida.

NOAA has a number of long-standing or recent mandates and legal requirements that are increasing the demand for mapping to be done in Florida, the southern Atlantic Ocean and the eastern Gulf of Mexico. Each group within NOAA has its own set of prioritized needs with an associated time frame in which information is required. NOAA must set priorities that balance the requirements of these numerous groups and meet the critical needs of the most users in a timely fashion.

The Coral Reef Conservation Act of 2000

The purposes of Coral Reef Conservation Act of 2000 are to:
(1) to preserve, sustain, and restore the condition of coral reef ecosystems;
(2) to promote the wise management and sustainable use of coral reef ecosystems to benefit local communities and the Nation;
(3) to develop sound scientific information on the condition of coral reef ecosystems and the threats to such ecosystems;
(4) to assist in the preservation of coral reefs by supporting conservation programs, including projects that involve affected local communities and nongovernmental organizations;
(5) to provide financial resources for those programs and projects; and
(6) to establish a formal mechanism for collecting and allocating monetary donations from the private sector to be used for coral reef conservation projects.

The Act includes any State of the U.S. that contains a coral reef ecosystem within its seaward boundaries, American Samoa, Guam, the Northern Mariana Islands, Puerto Rico, and the Virgin Islands, and any other territory or possession of the U.S., or separate sovereign in free association with the U.S., that contains a coral reef ecosystem within its seaward boundaries.

The Act defines the term `coral reef ecosystem' to mean coral and other species of reef organisms (including reef plants) associated with coral reefs, and the nonliving environmental factors that directly affect coral reefs, that together function as an ecological unit in nature.

The Act directs the Directs the Secretary of Commerce to develop a national coral reef action strategy, consistent with the purposes of Act in consultation with the Coral Reef Task Force, established under Executive Order 13089 (June 11, 1998).

Recently, NOAA has integrated several components of its Coral Reef Conservation Program into the Coral Reef Ecosystem Integrated Observation System (CREIOS). The goal of CREIOS is to better link coral ecosystem mapping with coral ecosystem and oceanographic monitoring to develop a better understanding of the interactions of these ecosystems.

Florida Keys National Marine Sanctuary

National Marine Sanctuaries Act, Florida Keys National Marine Sanctuary and Protection Act (1990). Managerial responsibility: Florida Keys National Marine Sanctuary: Final Management Plan/Environmental Impact Statement (1996) and Florida Keys National Marine Sanctuary: Final Supplemental Environmental Impact Statement/Final Supplemental Management Plan (2000) [note: for the Tortugas Ecological Reserve].

The Florida Keys extend over 360 km from Key Biscayne southwest to the Dry Tortugas (Chiappone, 1996a). Paralleling the Keys is the Florida Reef Tract, the third largest bank-barrier reef system in the world. The offshore bank reefs are semi-continuous and include the only emergent reefs off the continental U.S. During the 1980s, oil drilling off the Florida Keys was being considered. At the same time, there were reports of deteriorating water quality throughout the region. Also, scientists were investigating effects of coral bleaching, the mass die-off of the long-spined urchin, loss of live coral, a major seagrass die-off in Florida Bay, declines in reef fish populations, and the spread of coral diseases (NOAA, 1996). As a consequence of these circumstances and three consecutive, large ship groundings on the reef tract, the Florida Keys National Marine Sanctuary (FKNMS) was designated in 1990. The purpose of the Sanctuary is to protect and conserve the nationally significant natural and cultural resources of the area, including critical coral reef habitats (Causey et al., 2000). Partners in the management of the FKNMS are NOAA and the State of Florida.

In November 1990, President Bush signed into law the Florida Keys National Marine Sanctuary and Protection Act (FKNMS Act). Congress recognized the critical role of water quality in maintaining Sanctuary resources and directed the Administrator of the U.S. Environmental Protection Agency (EPA), in conjunction with the Governor of the State of Florida and in consultation with the Secretary of Commerce, to develop a comprehensive Water Quality Protection Program (WQPP) for the Sanctuary. Consequently, the State of Florida and NOAA developed an Interim Memorandum of Agreement that became effective in 1992 to promote and ensure co-trusteeship in implementing the FKNMS Act and the 1990 Florida Trustees Resolution (DOC 1996). To ensure coordination with appropriate Federal, State, and local government agencies and entities, an Interagency Compact

Agreement (1996) and other memoranda of agreement and understanding were developed. Federal agencies with jurisdictions that overlap or abut those of the FKNMS include the National Park Service and the U.S. Fish and Wildlife Service. State agencies that work closely with NOAA in FKNMS management include the Florida Department of Environmental Protection and the Fish and Wildlife Conservation Commission/Fish and Wildlife Research Institute.

NOAA's Fisheries Requirements

The Southeastern Fisheries Science Center of NOAA Fisheries works in close consultation with the South Atlantic, Caribbean, and Gulf of Mexico Regional Fisheries Management Councils to manage regional fisheries. Fisheries management mandates stem primarily from the 1996 Sustainable Fisheries Act (SFA), which amended the Magnuson Act (renamed the Magnuson-Stevens Fisheries Conservation and Management Act). These acts require not only conservation of species and habitat, but also responsible management of fisheries as an economic resource. Key provisions of the SFA for which mapping products are needed include determining, designating and conserving Essential Fish Habitats (EFH) and Habitat Areas of Particular Concern (HAPC) and implementing Fishery Management Plans (FMP) and regulations. Information is needed to support the management of and research on fisheries both near shore and in open water, including illustrating the extent of EFH and HAPC, determining the boundaries and number of Marine Protected Areas (MPA), and for display of the spatial and temporal distribution of fishery catch and effort in localized areas. In addition the NOAA Fisheries Office of Protected Resources (OPR) is charged with the implementation of the Endangered Species Act of 1973 (ESA) for marine and anadromous species.

The National Marine Fisheries Service, Southeast Fisheries Science Center also is responsible for reviewing Environmental Impact Statements for projects in southeast Florida. They need to have adequate map products available in order to properly assess impacts of development, dredging, pipeline construction, beach replenishment and other activities and make recommendations

NOAA's Coral Reef Requirements

The U.S. Coral Reef Task Force, established in 1998, has endorsed a plan to complete comprehensive coral reef ecosystem maps of the U.S. by 2007. NOAA's Coral Reef program, which was established to bring together the four NOAA line offices that work to conserve and protect coral reef ecosystems and to support the objectives of the Task Force, has to date provided significant funding to collect shallow water data using satellite and aerial sensing techniques and develop maps of the benthic habitats seen in these images. To date, shallow-water benthic habitat maps have been produced for Puerto Rico, the U.S. Virgin Islands, portions of the main Hawaiian Islands, the Northwestern Hawaiian Islands, American Samoa, Guam, and the Northern Marianas.

NOAA's Offices of the Coast Survey and Ocean Exploration

Two additional NOAA organizations with mapping needs or interests in the U.S. Atlantic are the NOS Office of Coast Survey (OCS) and NOAA's Office of Ocean Exploration. OCS has high priority areas with mapping requirements for safety of navigation in Florida and is in the process of improving nautical charts for critical ports in Florida (e.g., Tampa Bay). The NOAA Office of Ocean Exploration sponsors a wide variety of research efforts for their exploration and outreach programs and is also providing a significant amount of funding for mapping and collection of ground-truth information in the Atlantic, Caribbean, and Gulf of Mexico.

University and Other Federal Requirements

Federal agencies and university researchers are in need of the data and maps discussed here. For example, the U.S. Fish and Wildlife Service (USFWS) and National Park Service manage several National Wildlife Refuges and National Parks in the southern Florida. Numerous universities have extensive research and exploration programs that conducts marine biological, geological, and oceanographic research.

Florida Fish and Wildlife Conservation Commission (FWC)

Mandate-driven Requirements (Ch. 20.331, Florida Statutes)–Several Divisions of the FWC are specifically directed by statute to conduct work that would directly benefit from the mapping of South Florida's coral reef habitats. The first is the Fish and Wildlife Research Institute, which: a) Serves as the primary source of research and technical information and expertise on the status of marine life in Florida; b) Monitors the status and health of marine species and their habitat; c) Develops restoration and management techniques for habitat and enhancement of plant and animal populations; c) Provides critical technical support for catastrophes including: oil spills, ship groundings, major species die-offs, hazardous spills, and natural disasters; and d) Provides state and local governments with technical information and research results concerning fish and wild animal life.

A second FWC unit that would benefit from this mapping effort is the Habitat and Species Conservation Division which has duties supporting the management of public lands, habitat restoration on public lands, development and implementation of nongame species management plans, development and implementation of imperiled species recovery plans, providing scientific support and assistance on habitat-related issues, aquatic habitat restoration, habitat management assistance. The division uses scientific data to develop resource management plans that maintain stable or increasing populations of fish and wild animal life.

The third unit to benefit is the Marine Fisheries Management Division, which is tasked with developing recommendations for managing and enhancing commercial and recreational saltwater fisheries resources, implementing marine fisheries management programs, and assisting in the development and monitoring of artificial reefs in state waters.

Projects directly benefiting from coral reef mapping, including detailed bathymetry

Queen Conch Restoration–Queen conch, a protected species in Florida and CITES Appendix II species, has been depleted in Florida; consequently, Florida's efforts have focused on restoration of the population by transplanting adults into spawning habitats with the goal of increasing reproductive output of the population. Current benthic maps are not of sufficient resolution to assist in this effort; however, enhanced resolution of benthic habitat maps will permit the FWC to (1) predict where recovery should occur, and (2) identify additional optimal locations to establish new breeding aggregations.

Macroalgal distribution and abundance–High-resolution habitat and bathymetry for Martin, Palm Beach, and Broward Counties will complement information on macroalgal distribution and abundance, which are currently being collected by Harbor Branch scientists.

Spiny Lobster and Reef Fish Habitat Usage in Western Sambo Ecological Reserve–Using sonic technology, we have developed over 200,000 position estimates of over 40 spiny lobsters, red groupers, and yellowtail snappers in the Western Sambo Ecological Reserve. Movement patterns with respect to bottom features such as known patch reefs and the fore reef is being studied to evaluate the performance of the reserve and to understand how these species use the reef habitats of the Florida Keys. Unfortunately, less than 50% of Hawk's Channel in and around the Western Sambo Ecological Reserve and other protected areas has been mapped. The value of the data assembled for this project would be greatly increased if high-resolution habitat mapping were conducted.

Habitat Suitability Index Modeling–Habitat and depth are two of the main environmental parameters; in conjunction with salinity, and temperature, depth and habitat are used to predict the distribution of many vertebrate fish species. Detailed habitat maps and accurate depths (at sub-decimeter precision) would be highly beneficial and be of great value for determination of essential fish habitat.

Comprehensive Wildlife Conservation Strategy (CWCS)–In 2001, Congress established the Wildlife Conservation and Restoration Program to support the conservation and management of fish and wildlife species and their habitats. This program requires each state to develop a statewide CWCS. One of the elements required for each strategy involves describing the location and relative condition of the full suite of terrestrial, freshwater, and marine habitat types. Marine habitat maps describing the location of coral reefs and other marine habitat types are missing or lack sufficient detail for many parts of Florida waters. These maps are essential for prioritizing habitats for conservation and management of marine ecosystems for the CWCS.

Everglades Restoration–High-resolution habitat and bathymetry maps for Florida Bay and northern Keys will provide a baseline for the evaluation of habitat changes in that system resulting from the Everglades restoration efforts.

Finfish Monitoring–Visual surveys of fish using the ocean-side reefs throughout the Keys are conducted monthly to assess the trends of many harvested and ecologically important species. Many of these surveys use random-stratified sampling designs, which incorporate a habitat-based stratification process based on the existing benthic habitat maps of the Keys. These maps are missing large areas in both Hawk Channel and deeper waters where reefs are known to occur. Improving the resolution of existing mapped areas and mapping the unmapped areas will greatly improve the site selection process and reduce bias in the surveys. The net result will be improved information on the abundance trends of these fish that will help fishery managers determine the need for management action.

Coral Reef Management outside FKNMS–Inventory of these systems is critical to future management efforts, protection, and understanding restoration needs. For example setting up mooring buoys in St Lucie Inlet State Park.

Fishery Stock Assessments–Florida anglers spent an estimated $4.1 billion on fishing in 2001 and commercial landings made in Florida were valued at $175 million in 2002. Preliminary research shows that information on the dynamic interaction between fish distribution and fishing activity must be considered when managing many fish stocks for sustainable use. The distribution of fish associated with reefs and hard bottom is not readily measured but can be inferred from the distribution of habitats with some level of vertical structure.

Mapping of Coral Species Distribution–The Coral Reef Monitoring Program (CRMP) monitors change in coral species distribution, coral cover, and community composition. Among other things, corals require adequate light, and warm clear water. The effects of light and temperature are compounded with depth. Consequently, coral species distribution is strongly affected by depth. Slope and aspect, both derivatives of bathymetry, is of interest to us. Because of the requirement for light, any slope/aspect that will affect light attenuation at the coral surface will affect the rate of productivity and calcium deposition. Slope also plays a role in sedimentation. Sedimentation can cause stress in corals, especially those with small polyps. Consequently, small polyp species typically favor contours with steep slopes. Detailed bathymetry may help us define areas that are likely to support specific species of corals.

Locating Reef Fish Spawning Aggregations–Various snappers and groupers spawn in large aggregations. It is known that topographic features are one cue important to these fish. The topography in the outer reef areas of the Keys is poorly known. Subtle differences in benthic topography may be important to the Florida Keys in establishing spawning sites.

Complexity of Substrate–Substrate complexity may greatly affect the composition of benthic communities; for example, high diversity of reef fish assemblages is correlated with high topographic complexity. High-resolution bathymetry can be used to measure reef complexity. Such measures may allow researchers to predict relative reef productivity. This would aid permitting agencies in determining the effects of coastal construction projects on reef communities.

Artificial Reef Deployment–Habitat and Bathymetric maps are extremely useful in artificial reef deployment because the maps improve the efficiency and accuracy of site selection and provide information that aids in establishing buffers for natural hard-bottom.

Florida Department of Environmental Protection

The Florida Department of Environmental Protection is the lead agency in state government for environmental management and stewardship. The department administers regulatory programs and issues permits for air, water and waste management. It oversees the State's land and water conservation program, Florida Forever, and manages the nationally award-winning Florida Park Service. The department is the main architect of the $7.8 billion funding and management plan to restore America's Everglades – the largest water restoration project in the history of the world. The Florida DEP has a wide range of groups or programs that support the Department's objectives. Some are described briefly below. The Florida Department of Environmental Protection (DEP) is the governor-appointed point of contact agency for coral reef activities in the state of Florida, responsible for implementing Local Action Strategies in Florida which identify and address threats to local coral reefs and associated reef resources.

Coastal and Aquatic Managed Areas

Coastal and Aquatic Managed Areas (CAMA) manages 45 sites totaling nearly five million acres of submerged lands. All but four freshwater sites are located along Florida's 8,400 miles of coastline and include Aquatic Preserves, National Estuarine Research Reserves, and the Florida Keys National Marine Sanctuary.

Southeast Florida Coral Reef Initiative.

In 2003, with guidance from the U.S. Coral Reef Task Force, the Florida Department of Environmental Protection (FDEP) and the Florida Fish and Wildlife Conservation Commission (FWC) coordinated the formation of a team, comprised of marine resource professionals (state, regional, local, and federal), scientists, non-governmental organizations and other interested stakeholders to develop a Local Action Strategy (LAS) for Florida. The team targeted the northern extension of the Florida reef tract, which extends from Miami-Dade County, through Broward and Palm Beach Counties, to Martin County, using a facilitated process including public review and input. The southeast Florida region was chosen because its coral ecosystems are close to shore, co-exist with intensely urbanized areas and lack a coordinated management plan (like that of the Florida Keys National Marine Sanctuary).
The LAS, now known as the Southeast Florida Coral Reef Initiative (SEFCRI), developed through this process, was completed in December 2004, and addresses four areas of concern: (1) awareness and appreciation; (2) land-based sources of pollution; (3) fishing, diving, and other uses; and (4) maritime industry and coastal construction impacts. Shallow- water benthic habitat maps have been created to support the SEFCRI in Broward County and are planned and funded for Palm Beach County. However, benthic habitat maps are still needed for Martin County and Miami-Dade County, north of Biscayne National Park.

Florida Coastal Management Program

The Florida Coastal Management Program is based on a network of agencies implementing 23 statutes that protect and enhance the state's natural, cultural and economic coastal resources. The goal of the program is to coordinate local, state and federal agency activities using existing laws to ensure that Florida's coast is as valuable to future generations as it is today. Florida's

Department of Environmental Protection is responsible for directing the implementation of the state-wide coastal management program.

Resource Assessment & Management

The Division of Resource Assessment and Management provides scientific and technical support services to other department districts and divisions, and federal, state and local agencies. The Division includes the Director's Office, the Florida Geological Survey, the Bureau of Laboratories, the Mercury Program, and the Bureau of Information Systems.

The Mission of the Division of Resource Assessment and Management (DRAM) is to ensure maximum environmental protection through applied research and the effective integration and utilization of agency data. In order to accomplish this mission, we support quality management of information and research as a department resource; recognize the importance of information that is accessible, retrievable, and useable (reliable and valid); and seek to improve quality assurance while reducing the process burden on the department and the regulated community.

Division of Law Enforcement

The Division of Law Enforcement formed the Clean Boating Partnership to work with private organizations such as Marine Industries Association of Florida in their commitment to improving the health and cleanliness of our waterways. There is a direct link to the future of the marina industry and clean water. Clean water is necessary for the well being of our communities. If the waters are too polluted to recreate, then boaters will go elsewhere. To meet both the letter and the spirit of our state's environmental laws, our agency is in partnership with both private and public entities in the marine industry to develop a *Clean Marina Program.*

Florida's Clean Marina Program

There are nearly 2,000 marinas operating in Florida today and hundreds of thousands of boaters use Florida's waters every day. According to the Marine Industries Association of Florida, boating is a $14.2 billion dollar water intensive industry that includes marinas, boatyards and boaters. The effects of year-round boating activities contribute to constant and growing pressure on the state's fragile aquatic and marine ecosystems. Clean water is essential to this multi-billion dollar industry.

The aim of the Clean Marina Program (CMP) is prevention. Marinas and boaters may not be aware of the environmental laws, rules and jurisdictions with which they must comply. Compound that with the reality that environmental and operational problems are usually addressed after they happen rather than anticipated.

The goal of CMP is Clean Marina Designation. Designation lets boaters that use the marina know that these businesses adhere to - - or exceed program criteria, including *Marina Environmental Measures* or MEMs. MEMs are simple, innovative solutions to day-to-day marina operations that protect the environment. These MEMs have been developed through examination of best management practices around the country and the partnership of Florida's marinas, boatyards, boaters and government.

Voluntary participation, "pier" pressure and desire to do environmentally conscious activities and reinforcement of current regulatory processes are the common elements. This approach provides opportunities for public and private entities to work together, as well as, provide incentives and remove institutional roadblocks to wise resource stewardship. The text of these documents were written by the Department of Environmental Protection with intensive cooperative efforts of the Marine Industries Association of Florida, marine professionals throughout Florida and the United States, Florida SeaGrant, Boat US/Clean Water Trust, International Marina Institute, Florida Council of Yacht Clubs and local agencies.

The Florida FDEP Division of Law Enforcement also manages the grant programs for The Clean Vessel Act.